Optimized Breech Location in the Harry Diamond Laboratories 4-Inch Gas Gun

Herbert D. Curchack

U.S. Army Electronics Research
and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: HDL-TR-1983
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): Optimized Breech Location in the Harry Diamond Laboratories 4-Inch Gas Gun
5. TYPE OF REPORT & PERIOD COVERED: Technical Report
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Herbert D. Curchack
8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, MD 20783
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Materiel Development and Readiness Command, Alexandria, VA 22333
12. REPORT DATE: April 1982
13. NUMBER OF PAGES: 54
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES: HDL Proj: 898CH4
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Gas gun	Air gun	Kent
Helium gun	Pidduck	Ballistic
		Launcher

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A theoretical and experimental study was made to determine where a fixed length, constant diameter tube should be divided so that when one portion of the tube was used as a gun barrel and the remaining portion was used as a driver, the maximum projectile muzzle velocity would be obtained for a particular driver gas and initial projectile acceleration. Studies were made of several gas gun configurations, of 4-in. (10-cm) inside diameter and 100-ft (30-m) length, for muzzle velocities greater than 500 ft/s (150 m/s). Calculations were made by using the Lagrange theory for very low Mach numbers; the constant diameter, infinite reservoir theory for very high initial accelerations; and the Pidduck-Kent theory for other regimes. Experimental results and

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Cont'd)

theoretical predictions are compared for several gun divisions, helium and nitrogen drivers, and initial accelerations from 200 to 5000 g. For improved gun utilization, gun configurations are suggested to reduce exit gas pressure, to reduce the quantity of driver gas required, and to ease operation and improve (statistical) utilization of the gun without unduly affecting muzzle velocity. Although the results obtained are specific to the Harry Diamond Laboratories 4-in. gas gun, computer programs are included that may be applied to other gun geometries.

CONTENTS

FIGURES

FIGURES (Cont'd)

TABLES

1. BACKGROUND

Gas guns are used at the Harry Diamond Laboratories (HDL) to accelerate ordnance items to velocities typical of mortar, recoilless rifles, and artillery projectiles, that is, 400 to 4000 ft/s (120 to 1200 m/s). Test considerations often dictate achievement of the required velocity with the lowest acceleration (g) force exerted on the projectile while in the gun. This dictum necessitates the use of low driving pressures, and therefore long guns are needed to achieve the required velocities. These guns are installed in special purpose laboratory space, and the maximum gun length is limited by the dimensions of the building. The characteristics of the guns and the governing theories must be known to configure the guns so as to maximize the projectile velocity for the applied acceleration.

The gun used most often at HDL has a 4-in. bore and is the subject of this experimental and theoretical investigation. A large portion of the gun is located in a 5-ft (1.5-m)-high tunnel that runs the width of the building that it occupies. Several meters of each end of the gun extend into a "breech" room and a "muzzle" room. This gun can be configured in two ways (fig. 1). For many tests, velocities of 400 to 800 ft/s (120 to 240 m/s) are adequate. These are readily achievable in a 1-atm configuration. In the 1-atm gun, a pin restrained projectile seals one end of a barrel, a diaphragm seals the other end, and the barrel is evacuated (fig. 1a). Removal of the pin permits atmospheric pressure to accelerate the projectile down the barrel and through the diaphragm. When tests require higher velocities, a pressurized driver is required. The gun contains provision for a second pin downstream from the 1-atm pin. The breech end of the gun is sealed, and the section between this end of the gun and the projectile can be pressurized (fig. 1b). This configuration uses part of the gun length as driver and therefore shortens the length of the gun available as barrel.

Consider the four pressure-driven gun configurations shown in figure 2. In the uppermost gun (fig. 2a), the driver gas has no volume, and therefore the projectile can achieve no velocity. The projectile moves with increasing speed as the pin is located farther downstream (fig. 2b). Further movement of the pin (fig. 2c) shortens the barrel length (the distance over which the projectile accelerates) and thus offsets the gain in chamber volume. Finally, as the pin location nears the muzzle end of the gun (fig. 2d), the projectile has little distance over which to accelerate, and the muzzle velocity approaches zero.

The problem is to locate the pin at the position that, for any specified velocity, requires the lowest gas pressure. This is equivalently stated as the pin position that maximizes the projectile muzzle velocity for a given gas pressure. There are a limited number of pin

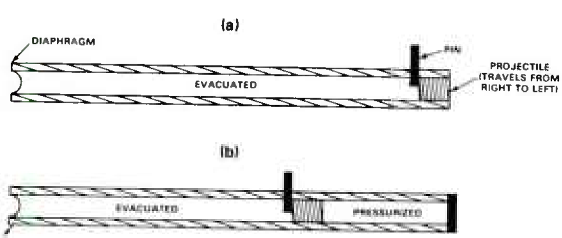

Figure 1. Four-inch gun: (a) one-atmosphere and (b) pressurized configurations.

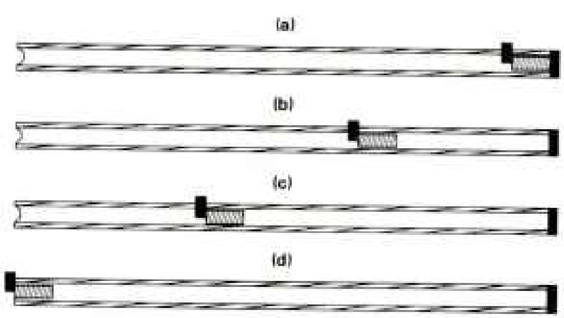

Figure 2. Four locations for release pin of constant length gun: (a) at breech, (b) near breech, (c) near muzzle, and (d) at muzzle.

positions (breech locations) in the 4-in. gun because of the way that the gun is constructed. This report shows that no one pin position is optimal for all velocities and, because it is impractical to relocate the breech for different tests, the solution to the problem becomes somewhat subjective.

2. CONSTRUCTION

The gun used in this investigation is constructed from eight 12-ft (4-m) lengths of 90-mm gun barrels. The barrels have been bored to a 4-in. (10-cm) inside diameter (i.d.), turned down to a 6-in. (15-cm) outside diameter (o.d.), and flanged. The barrel sections are always evacuated, even when a pressure driver is used. The joints are sealed with copper gaskets. The muzzle section of the gun (fig. 3) attaches to the last barrel and contains the fittings for the vacuum connections. This section has a large internal toroidal reservoir to accept any gas that is driven ahead of the projectile and thereby to minimize the pressure rise ahead of the projectile. This section contains also the muzzle seal, which is a 0.002-in. (50-μm) Mylar sheet clamped in a door by two screw latches. The Mylar is located on a roller above the door, and a new section of the sheet is pulled down and reclamped after each shot.

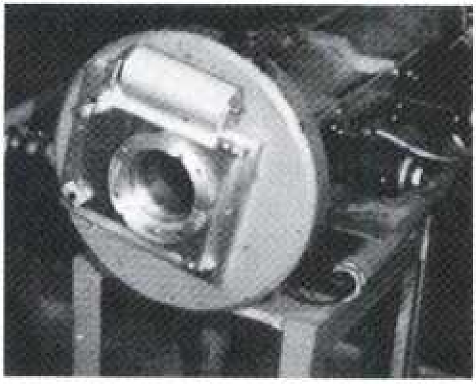

Figure 3. Muzzle section of 4-in. gun.

The release pin assembly used in the 1-atm configuration (fig. 4) attaches to the entrance of the first barrel. It is a short gun extension with an internal circumferential 0-ring groove to seal to the girth of the projectile and a pneumatically operated, electrically controlled pin to restrain the projectile. Also visible is a bac' ɲate, which acts as a backstop to capture the projectile if it is propelled out of the rear of the gun in the event that the muzzle diaphragm is accidentally ruptured. To the left of the release pin assembly is a side access port, which remains covered in the 1-atm configuration and is used only in the pressurized configuration.

In the pressurized configuration, the breech end of the gun is sealed by a closure section located in the side access port in the first barrel section (fig. 5). The closure section contains pressurization and vacuum ports.

The projectile restraining section used in the pressurized configuration (fig. 6) is 1 ft (30 cm) long; has a side access panel 8 in. long; and contains a pnuematically operated, electrically controlled pin and the required 0-ring. The projectile restraining section can be placed between any two sections of the gun and therefore can be placed at one of seven possible locations along the barrel. When the 1-atm configuration is used, the projectile restraining section 0-ring is removed, and the pin is withdrawn to allow free projectile passage through the projectile restraining section.

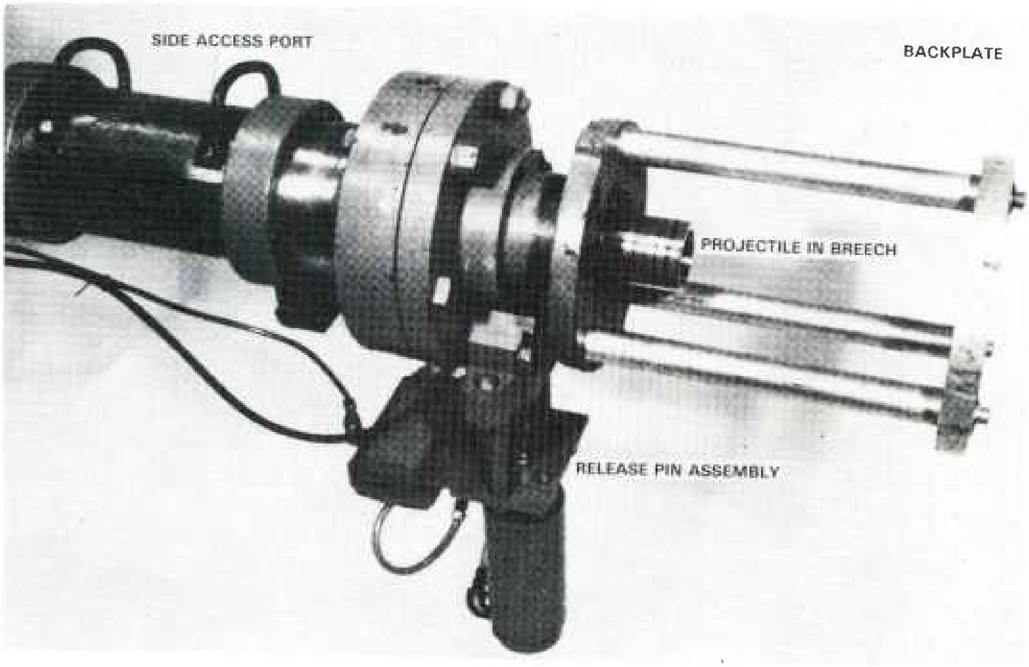

Figure 4. One-atmosphere configuration breech of 4-in. gun.

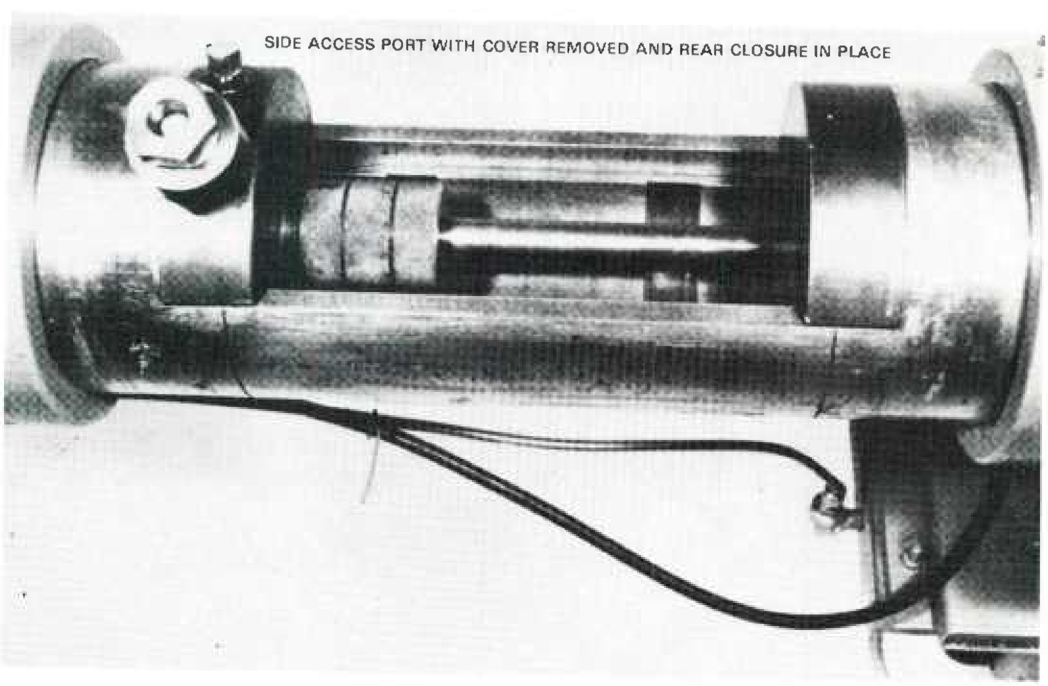

Figure 5. Closure section.

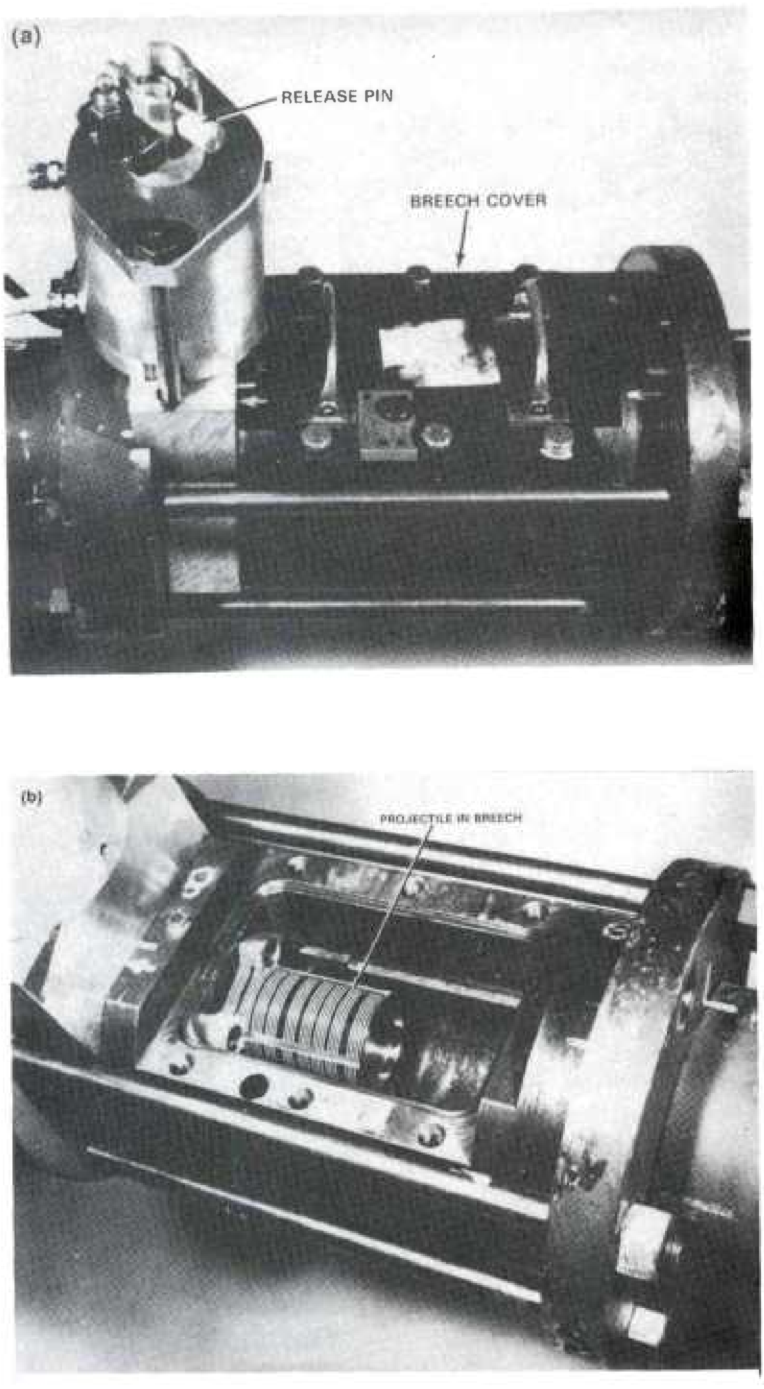

Figure 6. Projectile restraining section: (a) open and (b) closed.

The drawing in figure 7 shows the 4-in. gun with the projectile restraining section mounted between the first two barrel sections. This assembly provides easy access to the projectile restraining section because it is located in the breech room. Currently, the projectile restraining section is mounted between barrel sections 3 and 4 and is located in the gun tunnel. This location is somewhat inconvenient because of the low ceiling.

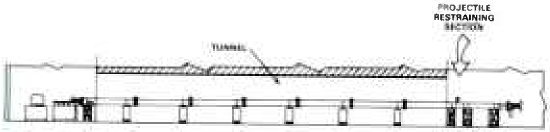

Figure 7. Isometric side view of 4-in. gun.

3. VELOCITY MEASURING INSTRUMENTATION

Muzzle speed is obtained by measurement of the time of flight between two "light screens" located 12.00 in. (30.48 cm) apart near the end of the last gun barrel section. All the experimental projectile muzzle velocity data presented below are computed by using these devices. For theoretical purposes, the end of the gun is assumed to be halfway between the two light screens.

Each light screen consists of a light source operated by direct current (dc), a photodetector, and an amplifier circuit. The source and the detector face each other along a diameter of the gun tube. When the projectile interrupts the light falling on the detector, a trigger signal is generated.

The light source consists of an incandescent lamp mounted behind an achromatic lens, which images the lamp filament about 200 mm in front of the lens. A lens in the detector assembly refocuses the light onto a small piece of frosted glass positioned immediately in front of the photodetector. With this arrangement, the photodetector amplifier output jumps from 2 to 18 V when the light beam is interrupted. The rise time of each detector and amplifier combination is 15 μs, with less than 1-μs difference between the two light screens. Therefore, time interval measurements are accurate to within 1 μs; positioning of the light screens is accurate to within 0.01 in. (0.25 cm); hence, the accuracy of the velocity measurements is approximately 0.4 ft/s (12 cm/s) at 400 ft/s (120 m/s) and about 6 ft/s (1.8 m/s) at 2500 ft/s (750 m/s).

Previous setups with finer beams and therefore finer distance resolution proved to be sensitive to debris or vibrations or both and occasionally triggered early. The present arrangement has proven to be highly reliable.

Streak photography, which is used to photograph the projectile shortly after it leaves the muzzle, provides a further check on muzzle velocity. The streak method (used for muzzle velocities less than 1500 ft/s or 300 m/s) agrees with the above method to better than 1 percent.

4. OTHER MEASUREMENTS

Other measurements that enter into the calculation of the initial acceleration are projectile weight, gas pressure, gun length, and gun diameter. By far, the least accurate of these measurements is the gas pressure, which is good to only 5 percent; hence, measurements of the initial acceleration are good to about 5 percent.

Certain gas parameters are used in the theory. The gas properties assumed are the properties of a pure gas at 20 C. The room (driver) temperature was constant to about 3 C, which has little effect on these properties. For nitrogen experiments, no special care was taken to assure driver gas purity. It was assumed that the air initially in the driver section was sufficiently close in properties to nitrogen so as not to influence the results. For helium shots, a purging technique was implemented consisting of three series of evacuation of the driver section to less than 5 psia (34.5 kPa absolute) followed by helium pressurizations to 50 psig (345 kPa gauge) (except for the final pressurization, which was to the required firing pressure).

5. THEORY

The problem of optimization of pin position in the 4-in. gun, along with a more general problem that includes diameter changes in the driver section, has been analyzed by Seigel.[1] Seigel's report contains an analysis of the four active HDL gas guns and two future guns. The aim of his investigation is to configure the guns so as to maximize the projectile velocity for a specified maximum projectile acceleration. The aim of HDL's investigation is stated in section 1.

5.1 *Isentropic Expansion*

It is instructive to start the theoretical discussion with a problem that is analytically tractable, adds insight to the results, and is shown to be valid for certain test conditions. Isentropic expansion of a driver gas[2] yields an approximate prediction of gun muzzle velocity (Lagrange approximation) when the gas sound speed is much larger than the projectile velocity (U), that is, small Mach number. It is assumed that the driver section diameter is the same as the barrel diameter.

$$U^2 = K[NZ(1 - Z^{2/N})/2] \ , \tag{1}$$

where

$$K = 2APL/M \ , \tag{1a}$$

$$Z = X/L \ , \tag{1b}$$

N is the degrees of freedom of the driver gas, A is the cross-sectional area of the gun barrel, P is the initial gas pressure in the driver reservoir, L is the total gun length, M is the projectile mass, Z is the relative position of the pin measured from the breech end of the barrel, and X is the length of the driver reservoir.

The square root of K is the velocity (U_{total}) that would be achieved in a constant acceleration gun of the total gun length.

$$U_{total} = K^{1/2} \ . \tag{1c}$$

The quantity in brackets in equation (1) is always less than 1 and therefore represents a decrease from U_{total}.

Since the ratio of barrel length (Y) to total gun length is 1 − Z,

$$U_{barrel} = U_{total}(1 - Z)^{1/2} \ . \tag{1d}$$

U_{barrel} is the velocity that would be attained if the acceleration were constant over the barrel length.

The optimum pin position (Z_{opt}) is found by differentiating U with respect to Z and setting the result to zero. These actions result in

$$Z_{opt} = (1 + 2/N)^{-N/2} \ , \tag{2}$$

$$U_{max} = U_{total}[Z_{opt}/(1 + 2/N)]^{1/2} \ , \tag{3}$$

$$U_{max} = U_{barrel}[N/(N + 2)]^{1/2} \times [Z_{opt}/(1 - Z_{opt})]^{1/2} \ . \tag{4}$$

Table 1 lists results from equations (2) to (4). Note these:

a. The greater the degrees of freedom of the gas, the shorter the driver and the higher the expected velocity.

[1] *Arnold E. Seigel, Performance Calculations and Optimization of Gas Guns, Chevy Chase, MD, HDL-CR-81-723-1 (May 1981).*

[2] *J. Corner, Theory of the Interior Ballistics of Guns, John Wiley & Sons, New York (1950).*

b. When the pin is located about 40 percent of the way down the length of the gun barrel, we should expect about 55 percent of the velocity achievable if the entire gun length were available for constant acceleration.

c. Velocity based on the actual barrel length indicates that the projectile can never achieve better than three-quarters of the constant acceleration velocity.

TABLE 1. FEATURES OF OPTIMIZED LAGRANGE GUN

N	Z_{opt}	U_{max}/U_{total}	U_{max}/U_{barrel}
3	0.465	0.528	0.722
5	0.431	0.555	0.736
Infinite	0.368	0.606	0.763

5.2 *Computer Analyses*

Theories that account for inertial effects of the gas were programmed in VAX-11 BASIC and are treated in the following sections. The programs are included in appendix A and are referred to as used in this paper. For ease of presentation, the results are in graphical form. The results obtained, although sometimes presented as dimensionless numbers, are not generally applicable. Guns of different lengths yield different curves as functions of the same dimensionless numbers. Such curves can be obtained only by changing the initial conditions in the programs.

5.3 *Pidduck-Kent Special Solution*

An important analytic treatment is the Pidduck-Kent solution, which assumes that through a number of reflections between the rear of the driver and the projectile, the flow has reached a steady pressure profile, which decreases in amplitude with time. The equations governing this solution are included in the program PDQ and are not repeated here.

In the following graphs, projectile velocity is presented as a function of relative pin position, that is, driver section length per total gun length. The parameter is the initial acceleration, which is the same as the maximum acceleration. Figure 8 presents results for a helium driver. The initial acceleration is 200 g for the lowest curve and 3000 g for the highest curve, and intermediate curves are in 200-g increments. Figure 9 shows the same results for nitrogen.

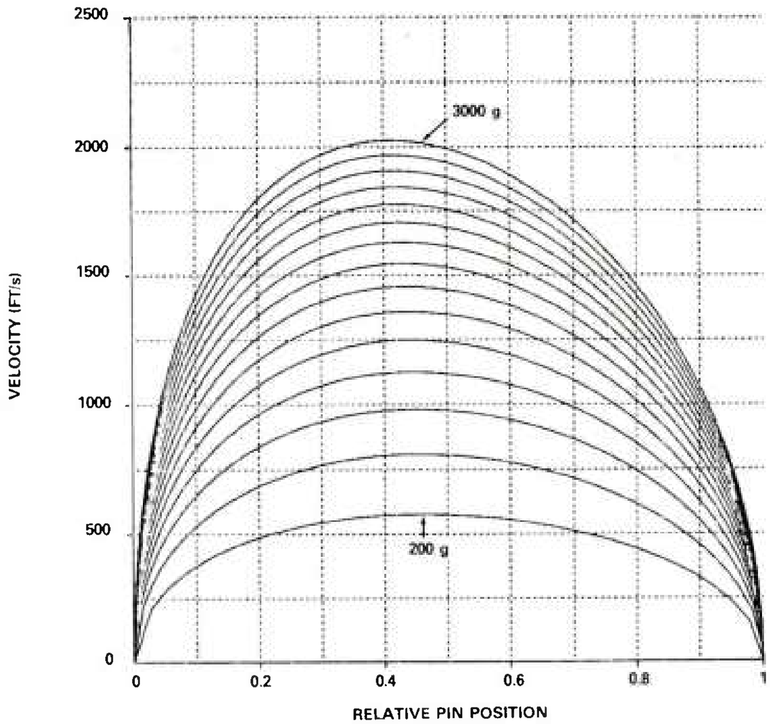

Figure 8. Pidduck-Kent theory, helium, 200 to 3000 g.

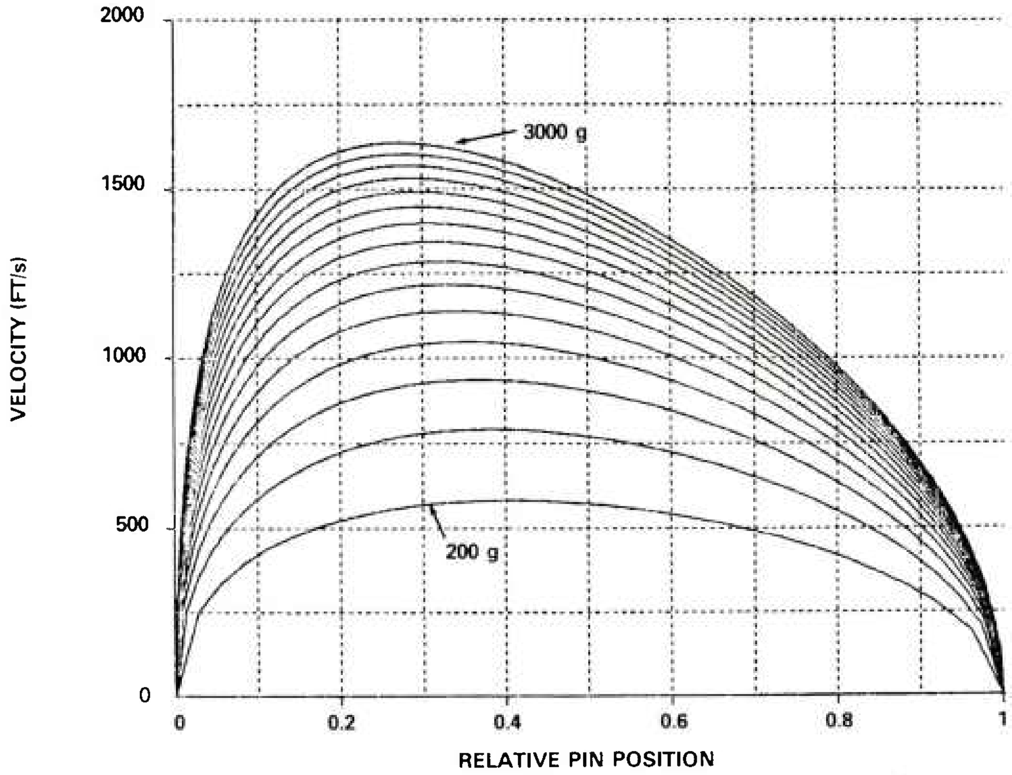

Figure 9. Pidduck-Kent theory, nitrogen, 200 to 3000 g.

Note that the relative pin position for the velocity peaks for the lowest curves in each figure, 0.467 and 0.417, fall near those predicted by the Lagrange theory in table 1. However, as the initial acceleration increases, the peaks shift to smaller values of relative pin position. The better agreement for the helium data is attributed to the assumption that a weightless gas, inherent in the Lagrange theory (which postulates infinite sound speed), is better satisfied; the Mach number for the 200-g helium case is only 0.15, but for the nitrogen case it is up to 0.5. The lowest curves (200 g) also predict velocities of 576 and 582 ft/s (173 and 175 m/s) for helium and nitrogen, that is, higher for nitrogen! However, as the initial acceleration increases, the higher sound speed of helium becomes of significance, and higher projectile velocities are obtained with the monatomic gas.

Figures 10 and 11 present data for initial accelerations of 3000 to 15,000 g in steps of 2000 g. Although accelerations of more than 3000 g are rarely anticipated for the particular application of this investigation,[3] these results are included for completeness.

[3] *Herbert D. Curchack, An Artillery Simulator for Fuze Evaluation, Harry Diamond Laboratories HDL-TR-1330 (November 1966).*

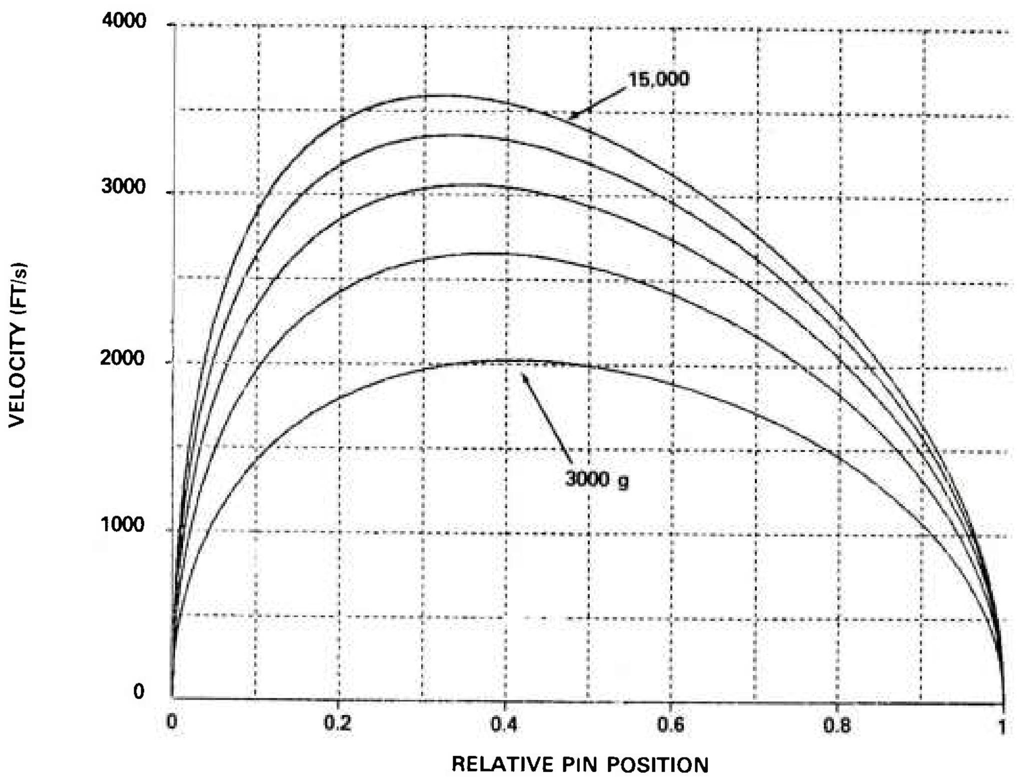

Figure 10. Pidduck-Kent theory, helium, 3000 to 15,000 g.

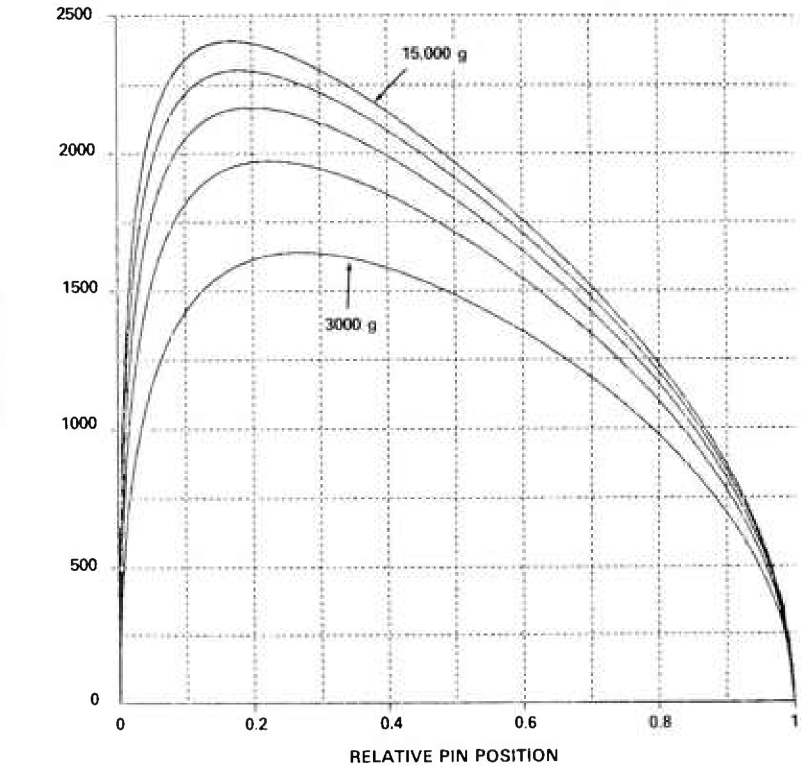

Figure 11. Pidduck-Kent theory, nitrogen, 3000 to 15,000 g.

5.4 *Constant Diameter, Infinite Length Driver Theory*

If the driver is assumed to be the same diameter as the barrel and infinite in length,[4] then program CONDIA is applicable. Although the governing equation can be deduced from the program, it is camouflaged by changes in notation and is repeated here.

$$PAY/Ma^2 = [u - N/(N+1)](1 - u/N)^{(N+1)} + N/(N+1), \quad (5)$$

where a is the initial sound speed in the driver reservoir and u is the projectile Mach number based on initial sound speed. This theory applies where the driver "appears" infinite. That is, when the first expansion wave (of an expansion fan) leaves the projectile at the onset of motion, the wave is reflected from the rear of the gun, but does not overtake the projectile before the projectile exits from the muzzle. The resultant curves are plotted in figures 12 to 15 for helium and nitrogen and for the lower and higher initial acceleration ranges.

The diamonds on the curves represent the projectile starting location for which the first reflected wave overtakes the projectile just as it leaves the muzzle. They were obtained from program CATCH. The assumption of infinite length driver is valid for all points to the right of the diamonds, and the validity decreases to the left.

These curves do not have theoretical maxima as in the Pidduck-Kent and Lagrange

[4]*Arnold E. Seigel, The Theory of High Speed Guns, Naval Ordnance Laboratory, White Oak, MD, AGARDograph 91 (May 1965), eq (12.2).*

cases. The optimum pin location from these curves is at a relative pin position of zero (Y = L), which is in a region in which the theory does not hold. (The driver is of zero length, not infinite length.) Therefore, a determination of optimum pin position from these curves is not possible. However, the first waves that overtake the projectile are weak expansion waves, and theoretical results that include effects of these waves would follow infinite driver results for some distance to the left of the diamond. Based on this consideration, the curves would continue to rise for some distance to the left of the diamonds, and optimum relative pin position would be to the left of the diamonds.

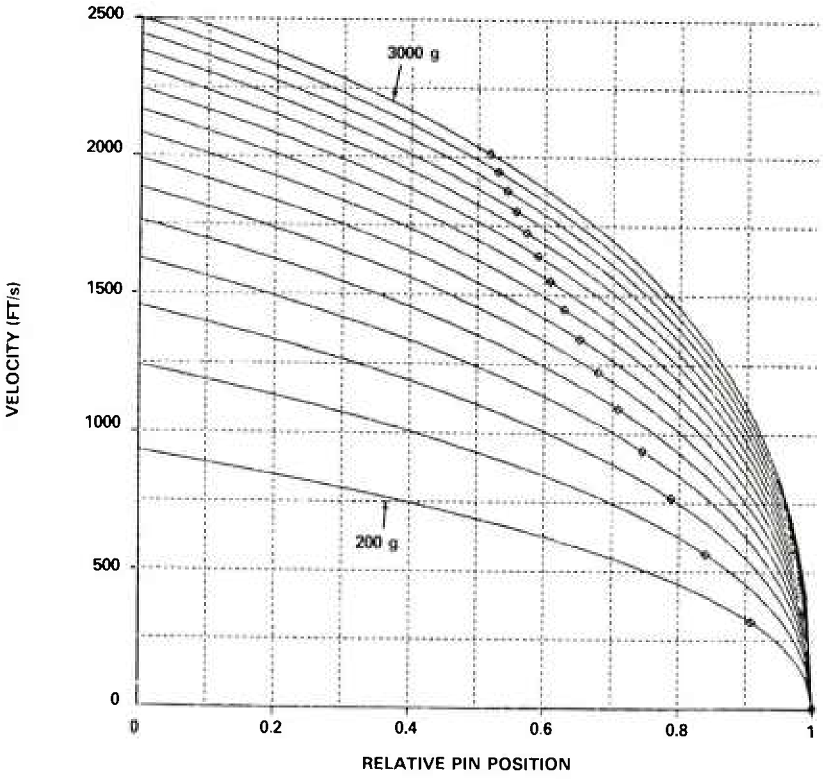

Figure 12. Infinite driver theory, helium, 200 to 3000 g.

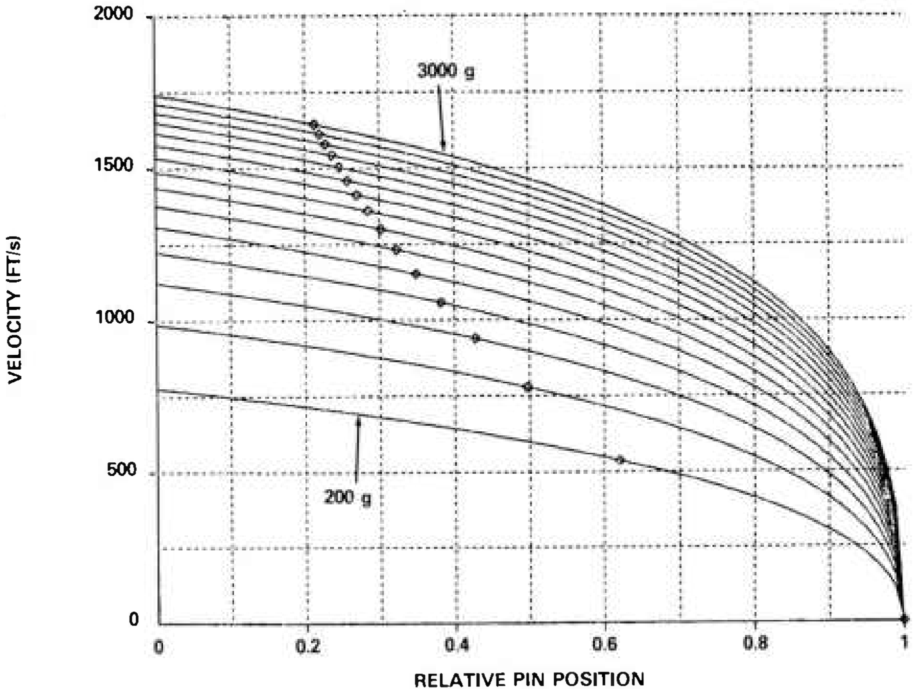

Figure 13. Infinite driver theory, nitrogen, 200 to 3000 g.

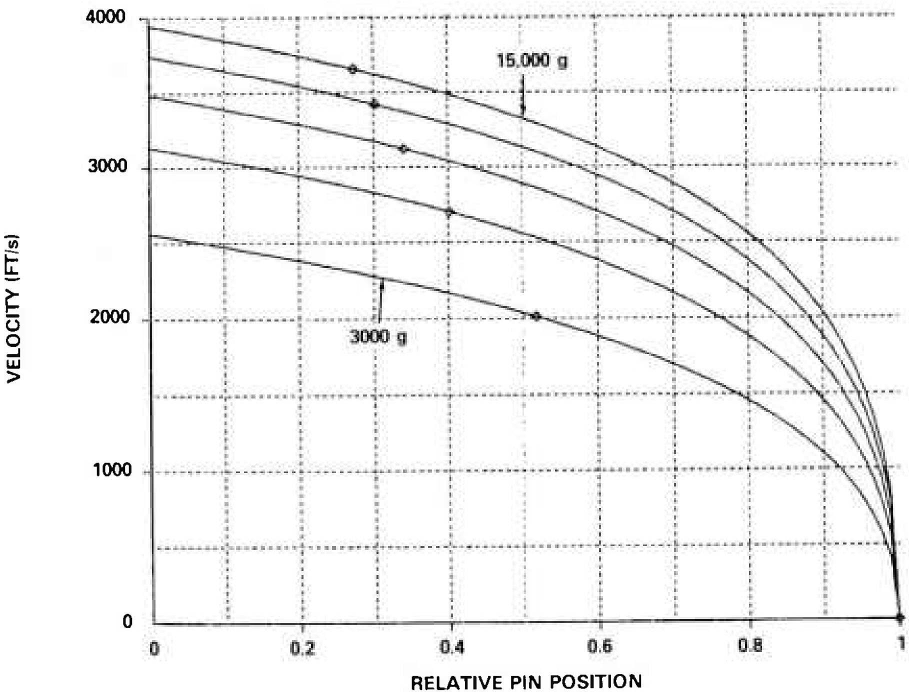

Figure 14. Infinite driver theory, helium, 3000 to 15,000 g.

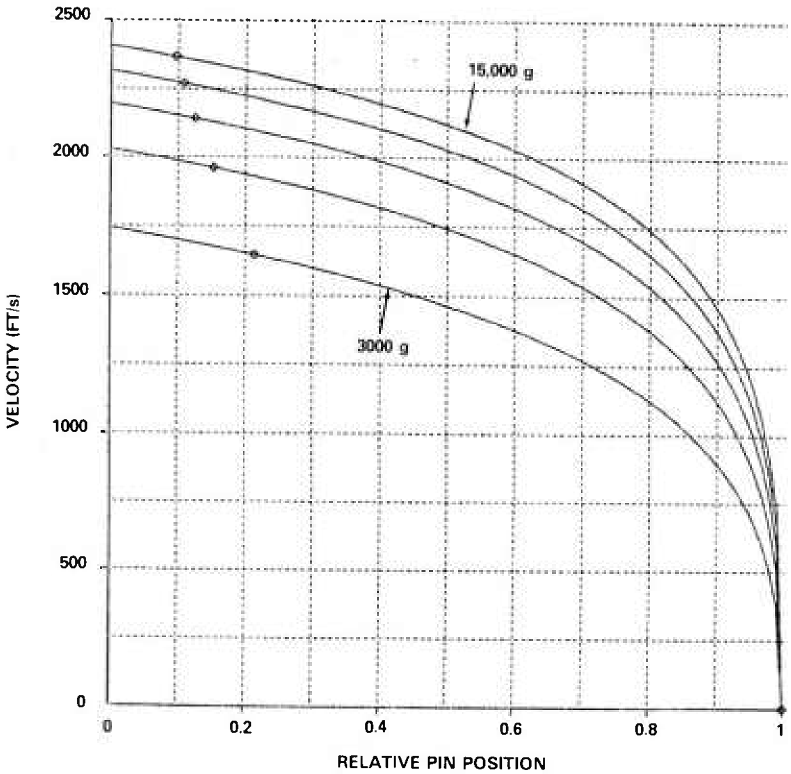

Figure 15. Infinite driver theory, nitrogen, 3000 to 15,000 g.

5.5 *Combined Pidduck-Kent and Infinite Driver Theories*

The results presented in figures 16 to 19 were obtained from program CDPK, which combines the results of Pidduck-Kent for small values of relative pin position with infinite driver results for large values. These were obtained by comparing the predicted velocities from the two theories starting at a relative pin position of zero and using the Pidduck-Kent result as output so long as it predicted a velocity lower than the infinite driver results. Once the infinite driver theory predicted lower velocity, infinite driver results were used for the remainder of the run, even though for higher values of relative pin position Pidduck-Kent again predicted lower muzzle velocity. Infinite driver results were used because infinite driver theory is more appropriate in this region. The point at which the two theories intersect is marked with a plus sign. The diamond represents the projectile starting location for which the first reflected wave overtakes the projectile just as it leaves the muzzle.

Generally, for low initial accelerations, the transition from one theory to the other is smooth, and the first reflection points are on or very close to the Pidduck-Kent portion of the curve. For higher accelerations, the transition becomes more abrupt, and the first reflection points lie above the Pidduck-Kent curves. Since infinite driver theory (sect. 5.4) implies that the maximum is to the left of the diamond, the conclusion drawn from these figures is that Pidduck-Kent underestimates muzzle velocity in the transition region, that is, where the first reflection overtakes the projectile near the muzzle. Since Pidduck-Kent assumes a gas pressure distribution that is achievable only after several reflections and infinite driver assumes no reflections from the projectile, this divergence is not unexpected. To use these graphs to predict optimum relative pin position now becomes difficult, especially for nitrogen. Although the curves have well-defined peaks, these peaks are in the region where the wrong theory defines the peaks. To reiterate, the "real" peak must be someplace to the left of the diamonds.

Another consideration in predicting velocity is associated with the very low Mach number region. For example, consider low initial accelerations with helium. The sound speed is sufficiently high so that many wave reflections occur while the projectile moves only slightly. This situation leads to a nearly uniform gas pressure between the projectile and the end of the breech. When the projectile remains at a low Mach number, the pressure drops uniformly in the driver section as the projectile moves and the volume increases. Under this condition, Lagrange results should be more appropriate than Pidduck-Kent results.

The net result of these theoretical considerations is that the velocity peak moves toward lower relative pin position with increasing initial acceleration, the peak is somewhere to the left of and near the diamonds, and the peaks differ in amplitude and location for helium and nitrogen. However, experimental results must be evaluated to verify the appropriateness and the range of any of the theories presented.

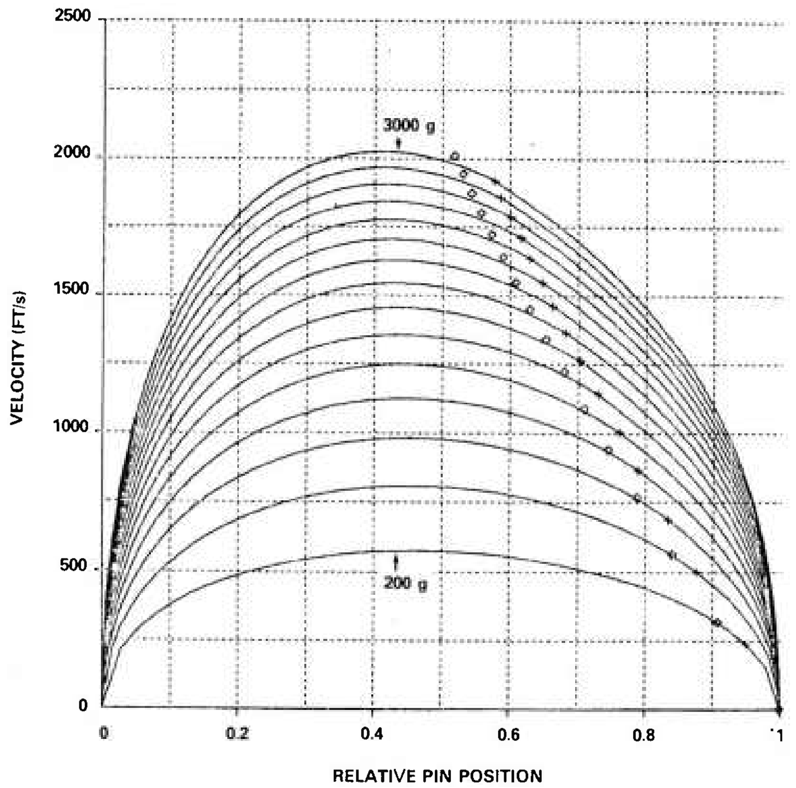

Figure 16. Pidduck-Kent and infinite driver theories combined, helium, 200 to 3000 g.

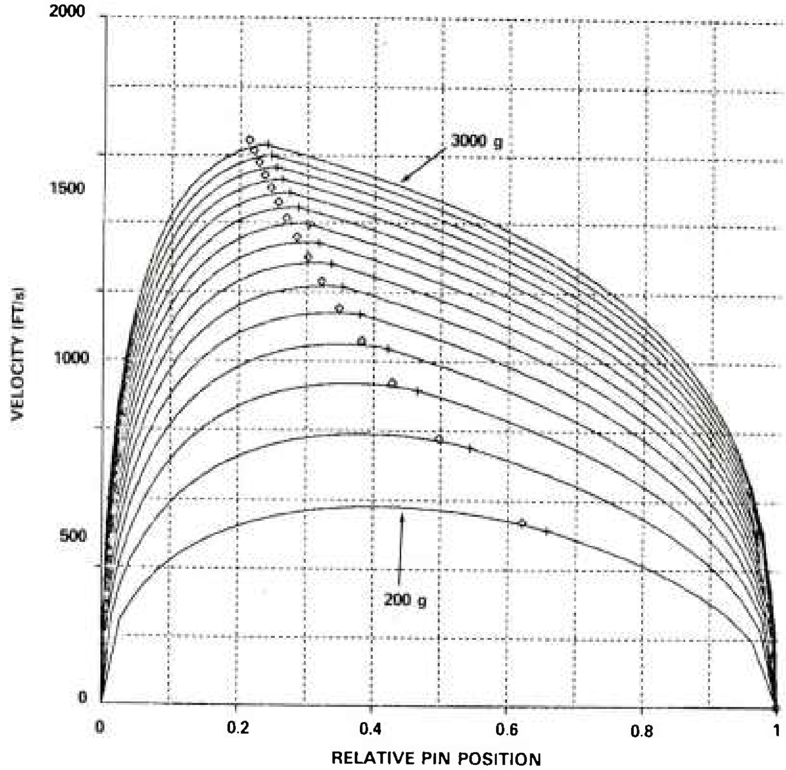

Figure 17. Pidduck-Kent and infinite driver theories combined, nitrogen, 200 to 3000 g.

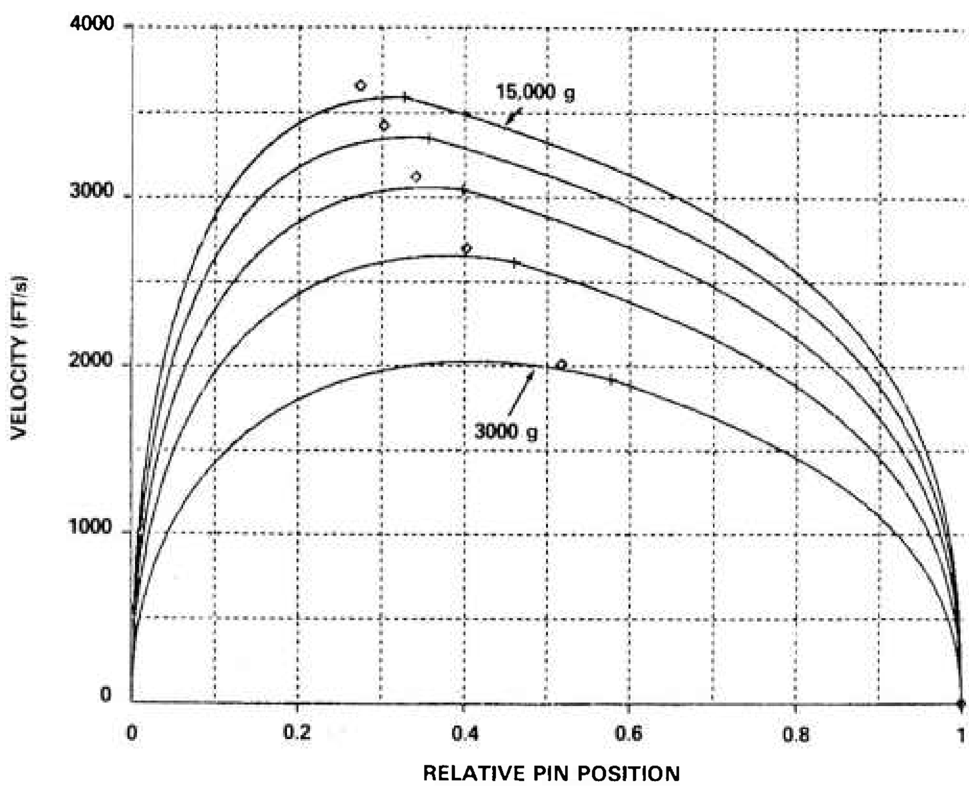

Figure 18. Pidduck-Kent and infinite driver theories combined, helium, 3000 to 15,000 g.

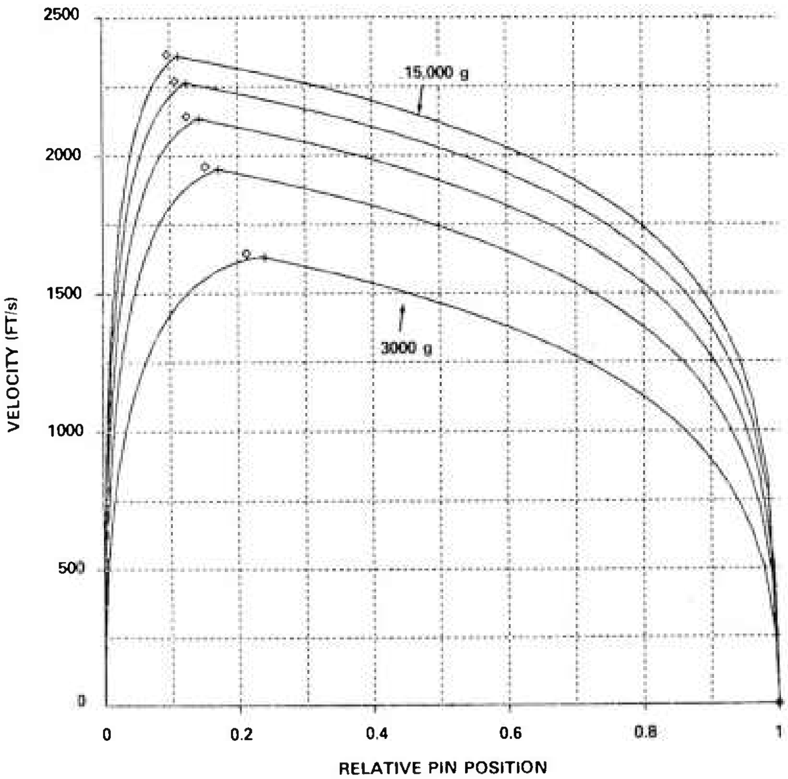

Figure 19. Pidduck-Kent and infinite driver theories combined, nitrogen, 3000 to 15,000 g.

6. EXPERIMENTAL RESULTS

6.1 *Procedure*

Many of the results included in what follows were made during routine operation of the gun. The projectiles were not specially prepared for optimum gun performance (fig. 20). Several projectiles were used. The most critical tolerances for these experiments, those associated with projectile diameter and the distance between the two bore riders (wheel base), were only grossly controlled. The projectile diameter ranged from 0.004 to 0.015 in. (102 to 381 μm) less than the gun i.d. The wheel base was typically 1 to 1.5 calibers. The center of mass of the projectile typically was near or aft of the rear bore rider.

6.2 *Data*

Experiments have been run with nitrogen with the projectile restraining section at two positions and with helium with the projectile restraining section at one of these positions. Maximum pressure was 300 psia (2070 kPa absolute). Projectile weights varied from 0.5 to 5 lb (0.25 to 2.5 kg) and covered the velocity range from 500 to 2600 ft/s (150 to 780 m/s). The first series of experiments had the projectile restraining section at the end of the first breech section; this was the easiest section to access. Sixty-nine shots were fired using nitrogen with the projectile restraining section located here. Subsequently, 229 tests with nitrogen and 94 tests with helium were run with the projectile restraining section between gun sections 3 and 4.

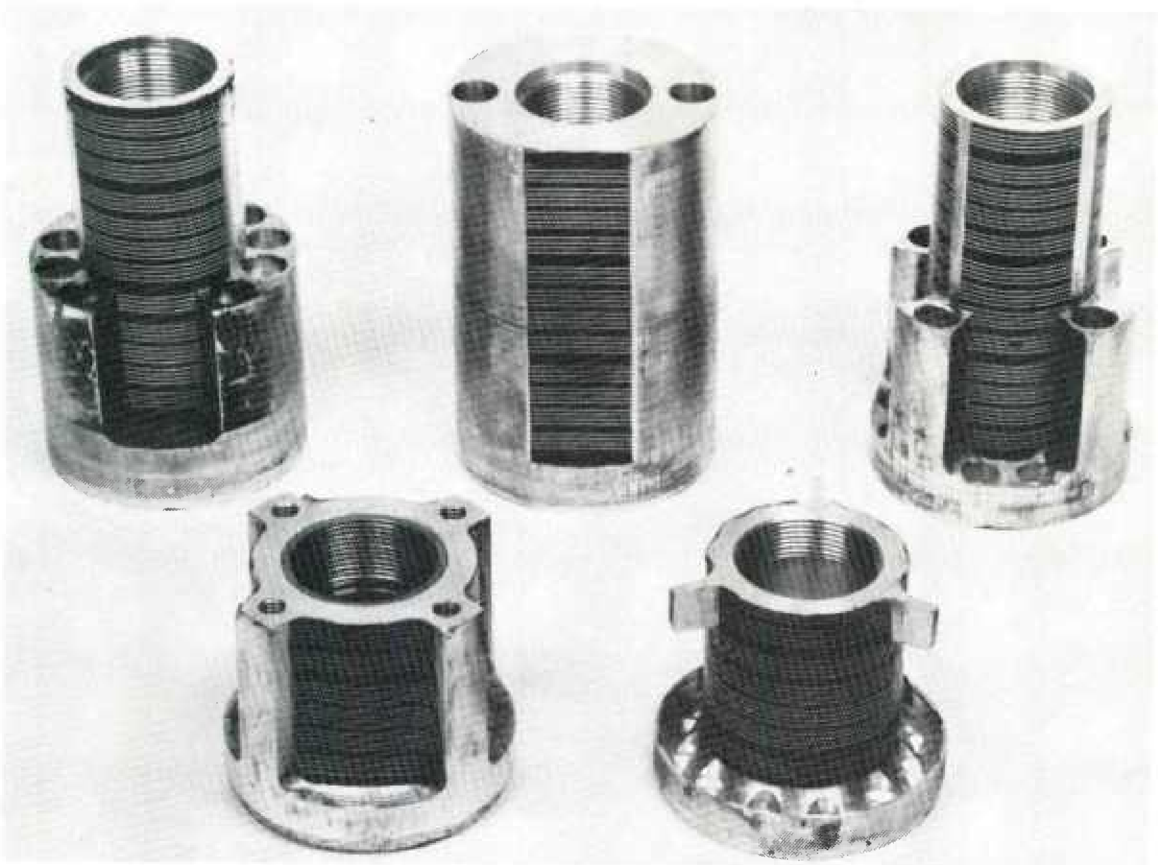

Figure 20. Typical projectiles used in study.

Each set of test data is plotted along with predictions from each of the three theories (fig. 21 to 23). The theoretical predictions were obtained from the program THEORY.

If the gun behaved as a constant acceleration gun, then the velocity would be proportional to the square root of the acceleration. Therefore, the x-axis in the figures was chosen to be the square root of the initial acceleration rather than the initial aceleration. This choice linearizes the results somewhat and eliminates a considerable amount of curvature from the plots.

The first set of results (fig. 21) represents the data for a nitrogen pressure driver, with the projectile restraining section between gun sections 1 and 2. This is a long barrel, short driver case with a relative pin position of 0.117. Each plus sign represents an experimental result. Except for an occasional "low" point, the data follow Pidduck-Kent theory. Referring to figure 17, a vertical line drawn at a relative pin position of 0.117 would intersect only Pidduck-Kent curves, regardless of initial acceleration.

Figure 22 shows the results obtained with a nitrogen driver and the projectile restraining section between gun sections 3 and 4. The relative pin position is 0.372. At initial accelerations up to about 1000 g, Pidduck-Kent is favored; above 1000 g, the results are closest to and within a few percentage points of infinite driver theory. Again referring to figure 17, a vertical line at 0.372 would intersect Pidduck-Kent curves up to 800 g and infinite driver curves for higher initial accelerations.

The third set of data (fig. 23) was based on a configuration that was geometrically the same as the last set, but the driver gas used was helium. In this set, Lagrange theory or Pidduck-Kent theory applies equally to the data below 1000 g. At higher acceleration, the data slightly exceed Pidduck-Kent theory. Reference to figure 16 at a relative pin position of 0.372 yields only Pidduck-Kent intersections up to initial accelerations of 3000 g. Figure 18 shows intersections with infinite driver only above 9000 g.

The combined experimental results are presented in figure 24 for comparison. The data of each set (delta, plus, and times symbols) are sufficiently separated from those of the other sets so that it is relatively easy to picture the trends associated with each. Experimental results at about 200-g initial acceleration show equivalent or slightly higher velocities for nitrogen compared with those for helium at the same projectile restraining section. As the initial acceleration increases, the superior results for helium are apparent.

The experimental velocities attained with nitrogen at a relative pin position of 0.372 exceed those at a relative pin position of 0.117 (fig. 24). However, the difference in velocities decreases with increasing initial acceleration. These two sets of data should eventually cross when the 0.117 gun acceleration is sufficiently large for infinite driver theory to govern. Then for larger initial acceleration, the longer barrel of the gun with a relative pin position of 0.117 (0.883) produces higher velocities than that with 0.372 (0.628).

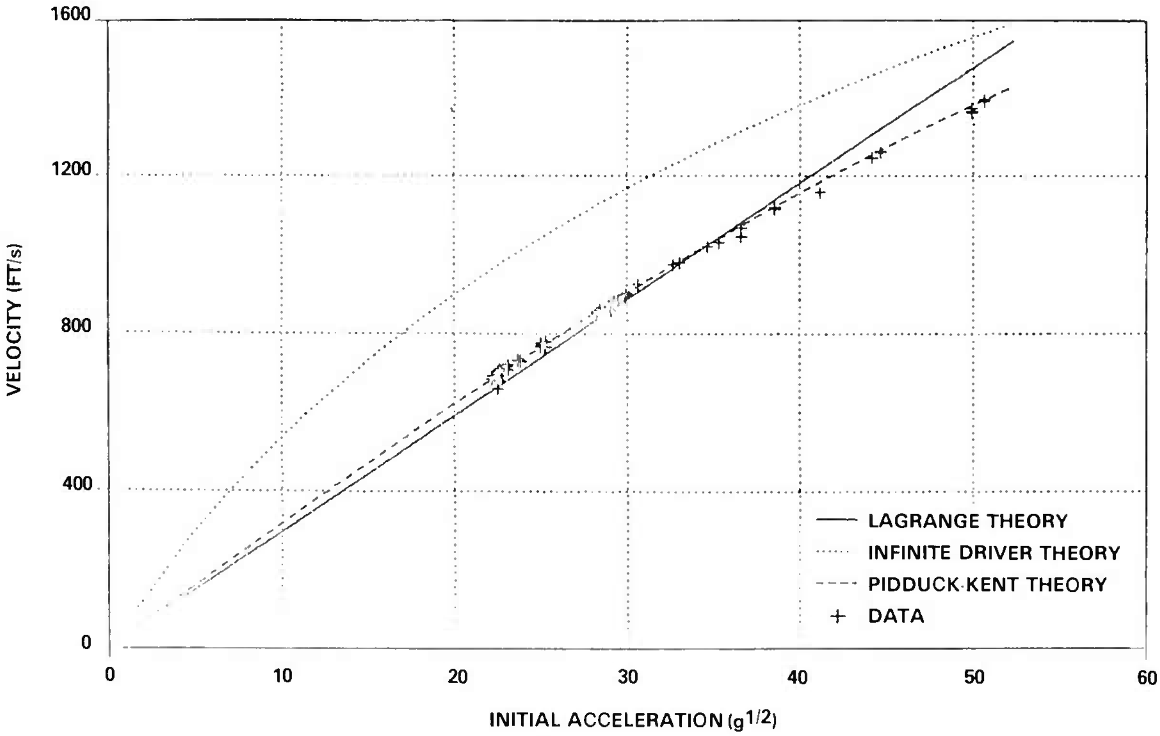

Figure 21. Data and theories, nitrogen, relative pin position of 0.117.

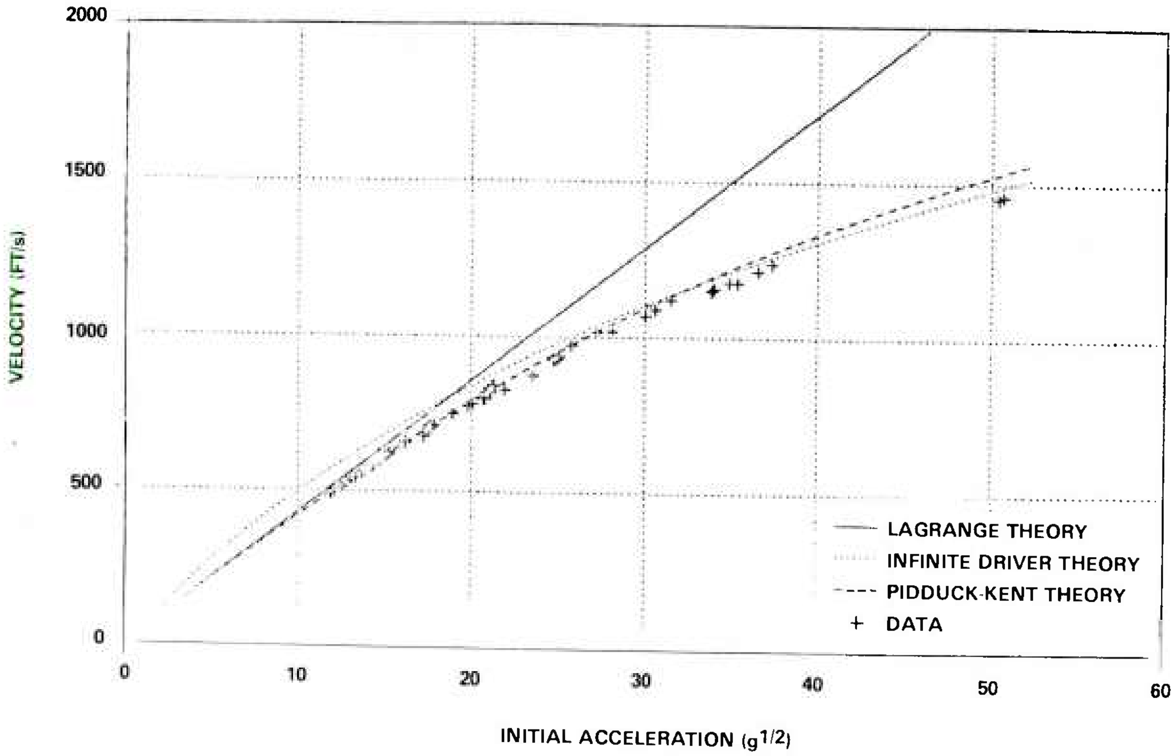

Figure 22. Data and theories, nitrogen, relative pin position of 0.372.

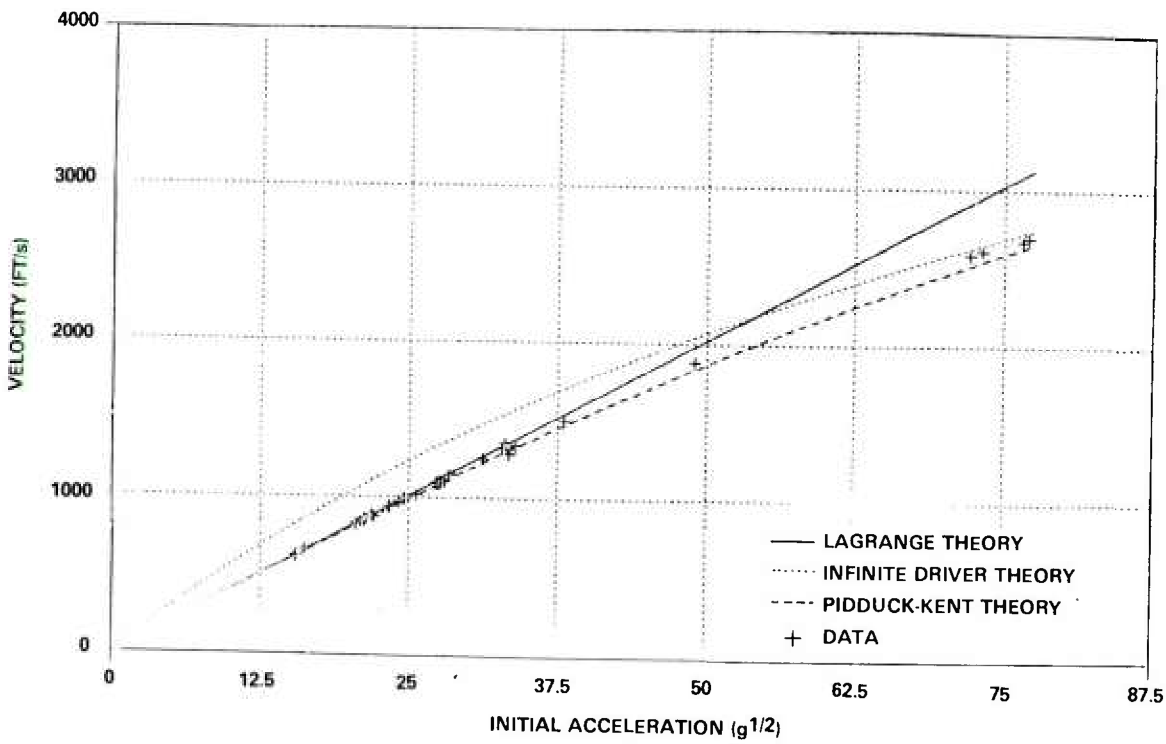

Figure 23. Data and theories, helium, relative pin position of 0.372.

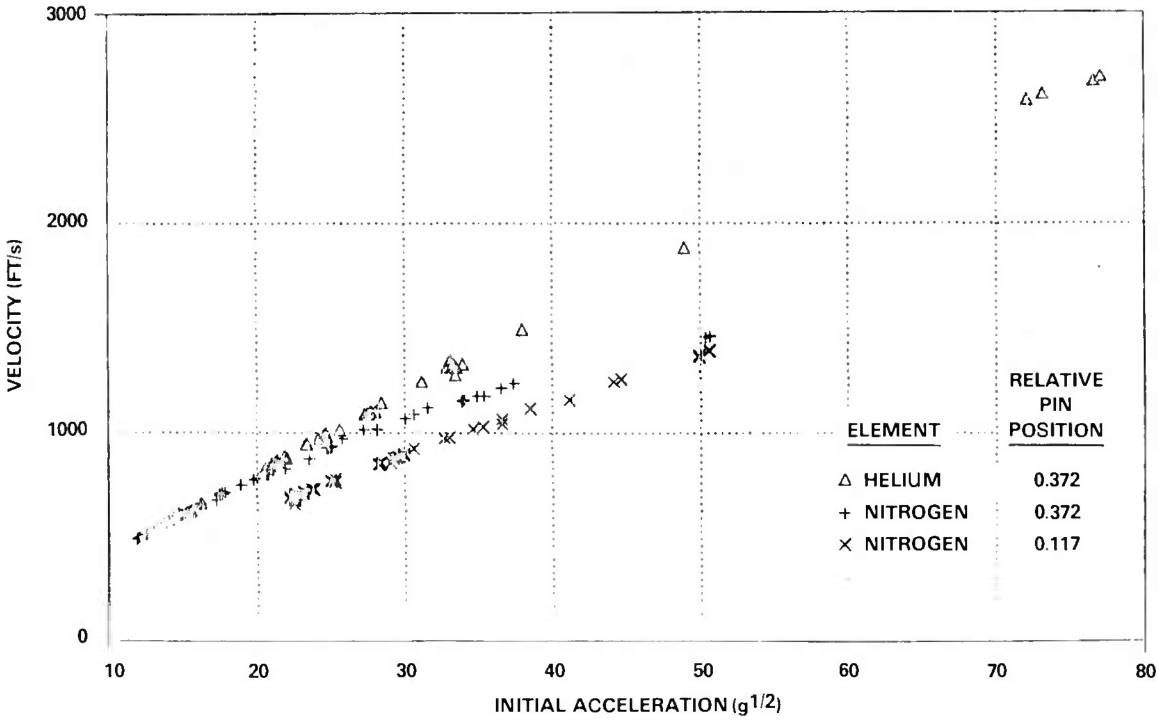

Figure 24. Combined data, nitrogen and helium, relative pin positions of 0.117 and 0.372.

7. DISCUSSION

The experimental data for helium show higher velocities than for nitrogen at the same initial accceleration for velocities above 750 ft/s (225 m/s) (fig. 24). Helium follows Lagrange theory or Pidduck-Kent theory for the lower velocities and Pidduck-Kent for velocities above 1500 ft/s (500 m/s) (fig. 23). From the assumptions associated with these theories, it follows that as the projectile restraining section is moved *away* from the muzzle (decreasing relative pin position), these theories should continue to be appropriate. (It is not clear that these theories will be appropriate if the pin is shifted *toward* the muzzle. In this region, the gun approaches an infinite driver configuration, and infinite driver theory may govern.)

No clear-cut optimum relative pin position has resulted from the experimental or theoretical investigation. Choice of relative pin position becomes a matter of judgment, which may be influenced by secondary considerations such as (1) expected range of use, (2) minimization of the volume (mass) of gas used, (3) minimization of the pressure behind the projectile at muzzle exit, and (4) ease of operation.

Figure 25 presents Lagrange curves and Pidduck-Kent curves for the first three possible projectile restraining section locations in the gun. Analysis of Lagrange theory readily yields the initial acceleration required at one projectile restraining section compared with the acceleration at a second projectile restraining section (acceleration ratio) to produce the same muzzle velocity. (From the form of the Pidduck-Kent equations, it appears that this acceleration ratio varies with the initial acceleration. Nevertheless, from the Lagrange curve and Pidduck-Kent curve shapes of figure 25, any generalization based on trends applicable to Lagrange theory is generally applicable to Pidduck-Kent theory in this acceleration regime.)

Consider the quantity (mass) of gas used per test as a secondary criterion. As an example, assume that helium is used and that the gun is operating in the Lagrange regime or the Pidduck-Kent regime. (If the acceleration is sufficiently high to operate in the infinite driver regime, then reducing the relative pin position increases muzzle velocity.) The gas required for a shot is immediately available from the gun dimensions and required initial pressure (acceleration) (program WTVSRPP).

Figures 26 and 27 show the mass of gas (relative to the projectile mass) required versus projectile restraining section location (relative pin position) for velocities from 300 to 1000 ft/s (90 to 300 m/s). A significant observation is that the minimum gas mass required is at a relative pin position of zero. (Although as the relative pin position approaches zero the required pressure becomes infinite, the volume and the mass go to zero.) The quantity of gas increases monotonically with increasing relative pin position. It is apparent that to minimize the amount of gas used, one would choose the smallest driver, whether it be helium (fig. 26) or nitrogen (fig. 27). This choice is important when the gun operates with helium because of the time involved in purging and filling the driver; that is, the smaller the driver and the less gas required, the faster the operation (firing).

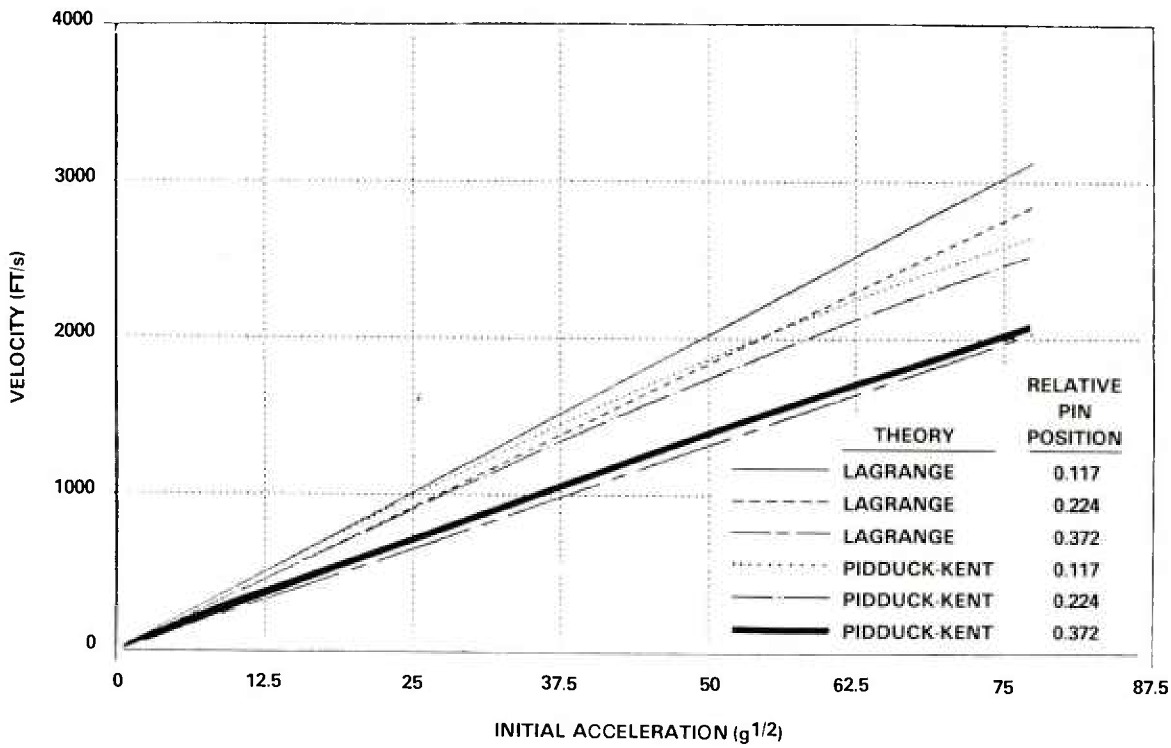

Figure 25. Lagrange and Pidduck-Kent theories, helium, relative pin positions of 0.117, 0.244, and 0.372.

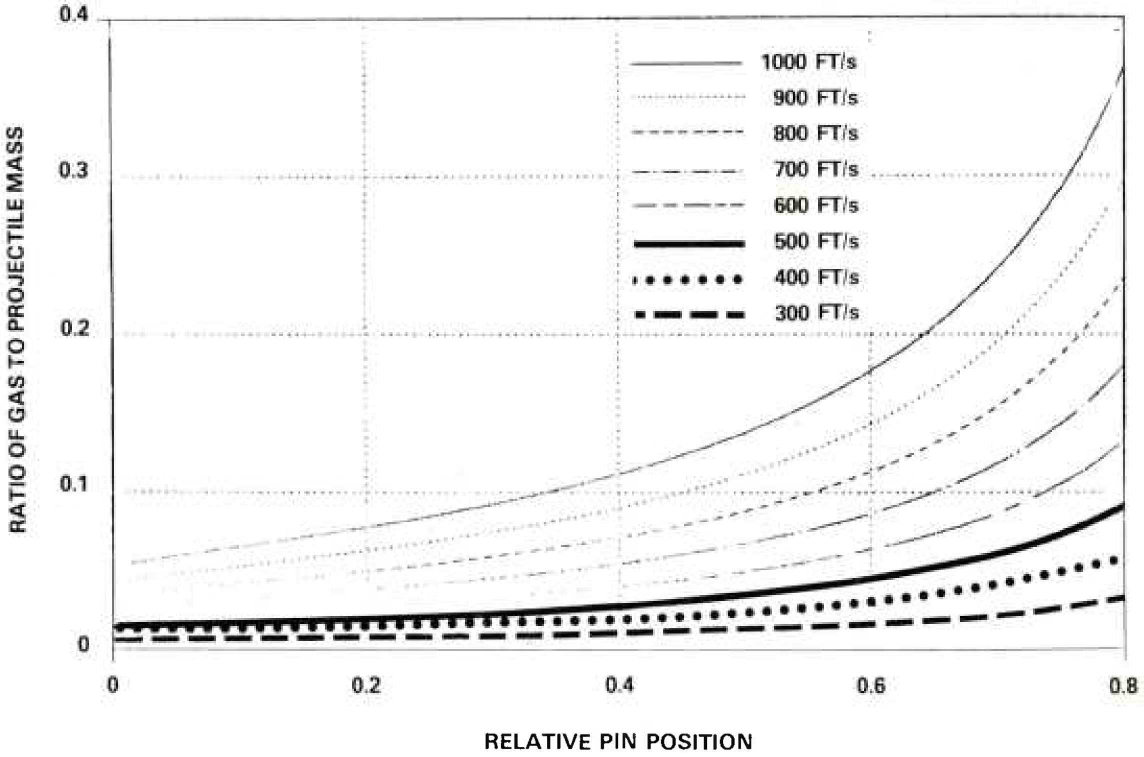

Figure 26. Helium (Lagrange theory).

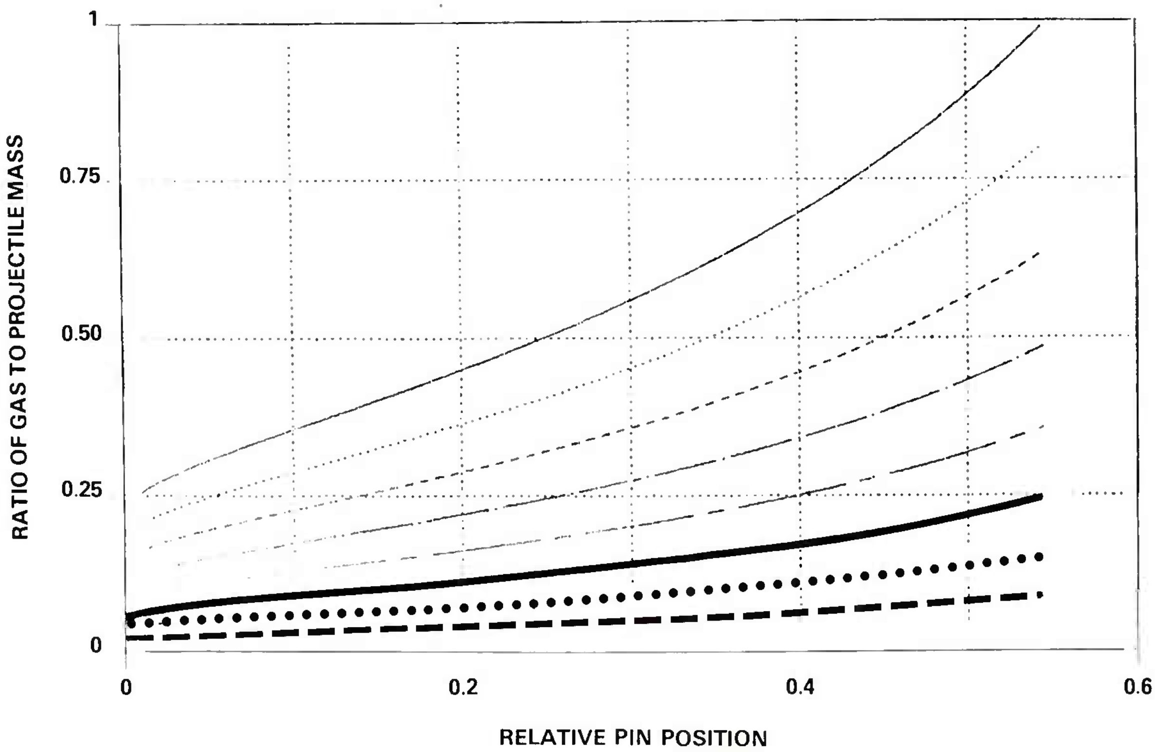

Figure 27. Nitrogen (Lagrange theory).

Another consideration is the amount of energy stored in the gas when the projectile exits from the gun. This energy may damage equipment or interfere with the impact experiments. The theory presented in program NRG predicts the energy transferred from the driver gas to the projectile. The final driver gas energy (enthalpy) was obtained by subtracting the projectile muzzle energy from the initial gas energy. The results (fig. 28) show that the smaller the driver (small relative pin position), the greater the amount of energy transferred to the projectile and therefore the smaller the amount of energy remaining in the gas. (Note: The greater the degrees of freedom of the gas, the less energy transferred to the projectile.)

The effects of projectile restraining section placement on several parameters are presented in table 2. The five projectile restraining section locations are nearest the breech. The effects are arbitrarily referenced to the present pin location (between sections 3 and 4). For example, the initial acceleration required to produce a particular muzzle velocity for a projectile restraining section between sections 3 and 4 is assigned a value of 1. The initial acceleration required to produce the same velocity for the pin between sections 1 and 2 would be 2.02 times as great (table 2, second parameter).

Note that the fourth pin position (relative pin position of 0.500) is close to the optimum location based on Lagrange theory (relative pin position of 0.465, helium, table 1). Table 2 indicates that moving the pin to this position reduces the initial acceleration by only 3 percent, but requires 30 percent more gas. If a 21-percent increase in initial acceleration is tolerable, then gas usage can be cut 21 percent by moving the projectile restraining sec-

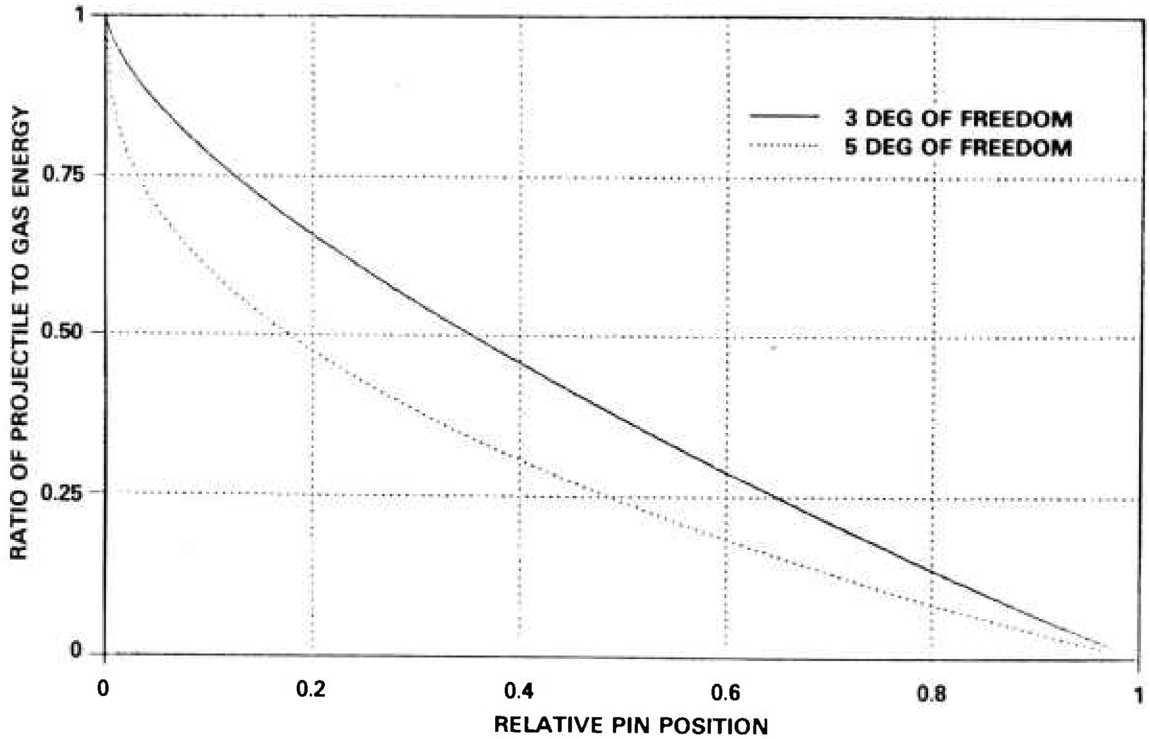

Figure 28. Fraction of energy gained by projectile from driver gas (Lagrange theory).

tion back one section. Moving the projectile restraining section back two sections to its original location is not as attractive.

The data of the fourth parameter of table 2 show that there would be a 24-percent reduction in gas energy at breech exit by moving the projectile restraining section back one section.

8. CONCLUSIONS AND REMARKS

A theoretical and experimental study was made to determine where a fixed length, constant diameter tube should be divided so that when one portion of the tube is used as a gun barrel and the remaining portion is used as a driver (chamber), the maximum projectile muzzle velocity can be obtained for a particular driver gas and initial acceleration. Studies of several HDL 4-in. gas gun configurations indicated that no one configuration is best for all velocities greater than 500 ft/s (150 m/s), the range of interest. (For lower velocities, the gun is used in the 1-atm configuration, where the entire tube length is used for the barrel and ambient air is the driver. This configuration is not relevant to the study.)

For the cases considered (short driver versus long driver, helium versus nitrogen, and initial accelerations from 200 to 5000 g), the experimental results generally follow different theories in different operating regimes: Lagrange theory in the very low Mach number regime, infinite driver theory in the very high acceleration regime, and Pidduck-Kent theory in other regimes. Although the various results are explicable in terms of the postulated theories, no one theory accurately predicts the entire range of experimental results. Therefore, it is difficult to infer a general optimum configuration because theoretical predictions around the optimum are in most cases conflicting or poorly defined or both. Because no clear-cut division of the tube can be inferred to optimize muzzle velocity, secondary criteria such as quantity of gas required, energy remaining in the gas, (statistical) utilization of the gun, and ease of operation can influence the configuration without unduly affecting muzzle velocity.

In conclusion, significant savings in gas usage and reductions in gas energy at muzzle exit can be realized with only a small acceleration penalty by reconfiguring the HDL gun to a one section longer barrel and one section shorter driver.

TABLE 2. EFFECTS OF PROJECTILE RESTRAINING SECTION WITH HELIUM DRIVER

Parameter	Projectile restraining section between sections				
	1 and 2	2 and 3	3 and 4	4 and 5	5 and 6
Relative gun position	0.117	0.245	0.372	0.500	0.628
Initial acceleration ratio to attain particular muzzle velocity	2.02	1.21	1.00	0.97	1.07
Ratio of required gas masses	0.63	0.79	1.00	1.30	1.81
Ratio of final driver gas energy to initial gas energy	0.46	0.76	1.00	1.22	1.42

Note: Reference is projectile restraining section location between sections 3 and 4; relative pin position is 0.372.

ACKNOWLEDGEMENT

The author extends his appreciation to Forrest Nelson, William McIntosh, and Robert Kayser for their careful performance of the experiments and their faithful recording of the data.

NOMENCLATURE

a	Initial sound speed in driver reservoir
A	Cross-sectional area of gun barrel
K	2APL/M
L	Total gun length (barrel + driver, X + Y)
M	Projectile mass
N	Degrees of freedom of driver gas: N = 3 for helium and N = 5 for nitrogen
P	Initial gas pressure in driver reservoir
u	Projectile Mach number based on initial sound speed (U/a)
U	Projectile velocity
X	Length of driver reservoir
Y	Length of barrel
Z	Relative pin position in gun (X/L)

APPENDIX A.—COMPUTER PROGRAMS

The computer programs on the following pages were written in VAX-11 BASIC, a compilable, native mode language. Since the language is not as restrictive as standard BASIC, a few of the major differences are pointed out for those who wish to adapt the programs to their own computers.

Comments.—In addition to REM statements, the exclamation point serves as a comment delimiter.

Example:

```
10 THIS=THAT    ! SET THE VARIABLE THIS EQUAL TO THE VARIABLE THAT
```

Continuations.—A line may be continued on the following line when the last character on the line to be continued is an ampersand.

Example:

```
10 THIS= &
THAT
```

Multiline statements.—Statements to be executed in continuous order can be on the same line if they are separated by a back slash.

Example:

```
10 THIS=7 \ THAT=8
```

Line numbers.—Line numbers are not required if the statement is indented at least one character from the left margin. Lines are executed in order.

Example:

```
10 THIS=7
   THAT=8
```

Variables.—Names of variables are allowed to be up to 32 characters long and can contain most ASCII characters.

Example:

```
10 DEG.OF.FREEDOM=2/(GAMMA-1)  \  AVG_A=SUM_A/NO
```

Use of these enhancements produced programs that are easier to read and to follow than standard BASIC. The programs included are PDQ, CONDIA, CATCH, CDPK, THEORY, WTVSRPP, and NRG. Other programs were used to retrieve the data from the record files and to plot the data. However, these are not general and would be of little use to the reader.

```
10 REM^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
                              PDQ.BAS
                    APRIL 1980    H D CURCHACK

                       PIDDUCK-KENT THEORY
               SEE SEIGEL  HIGH SPEED GUNS PP 180-181
   ______________________________________________________________________

20      DIAM=4  ! IN. !                   \      X_SEC_AREA=PI*DIAM^2/4
        GAS$(1)="HELIUM"                  \      GAS$(2)="NITROGEN"
        SPEED(1)=3300   !FT/SEC!          \      SPEED(2)=1145
        DEG_OF_FREEDOM(1)=3               \      DEG_OF_FREEDOM(2)=5
        GAMMA(1)=5/3                      \      GAMMA(2)=7/5
        THISSTEP=500                      \      DEL_MU=1/THISSTEP
        TOTAL_L=94

30 FOR GAS=1 TO 2 \ PRINT GAS$(GAS)
        NO=DEG_OF_FREEDOM(GAS) \ CO=SPEED(GAS) \ GAMA=GAMMA(GAS)
        GAS_STEP(1)=.0005 \ GAS_STEP(2)=.0025

        OPEN "PK."+LEFT$(GAS$(GAS),3) FOR OUTPUT AS FILE #GAS
        GOSUB 40 FOR INIT_G=200 TO 3001 STEP 200
        CLOSE #GAS

        OPEN "PK1."+LEFT$(GAS$(GAS),3) FOR OUTPUT AS FILE #GAS
        GOSUB 40 FOR INIT_G=3000 TO 15001 STEP 3000
        CLOSE #GAS
    NEXT GAS
    GOTO 90

40      ! PIDDUCK KENT SUBROUTINE
        ! -----------------------

        PRINT "INITIAL G =";INIT_G       ! TERMINAL OUTPUT DURING RUN

        !   A_BAR IS A PARAMETER USED BY SIEGEL TO DETERMINE G/M AND VEL

        FOR A_BAR=0 TO 1 STEP GAS_STEP(GAS)
                ! INTEGRATION !
                INTGRAL=0
                FOR INTVAL=0 TO THISSTEP
                        MU=INTVAL*DEL_MU
                        F_OF_MU=(1-A_BAR*MU^2)^(NO/2)
                        INTGRAL=INTGRAL+F_OF_MU
                NEXT INTVAL
                INTGRAL=(INTGRAL-.5*(1+F_OF_MU))/THISSTEP
                        ! INTEGRATION COMPLETE !

                G_OVER_M=(NO+2)*A_BAR*(1-A_BAR)^(-(NO+2)/2)*INTGRAL

50 REM          - CONVERT G_OVER_M TO INIT_G AND DRIVER_L -
                        CO^2=GAMA*P/RHO
        ALSO
                        WEIGHT OF GAS (G)=RHO*X_SEC_A*DRIVER_L
```

```
                        DRIVER_L=G/(RHO*X_SEC_A)
                                =G*CO^2/(GAMA*P*X_SEC_A)
                                =G*CO^2/(GAMA*INIT_G*M)
        THEREFORE
60                DRIVER_L=G_OVER_M*CO^2/(GAMA*INIT_G*32.2)
                  FRAC_L=DRIVER_L/TOTAL_L
                  IF FRAC_L>1
                     THEN 80
                     ELSE VEL=2*CO/(GAMA-1)*SQR(A_BAR*(1-FRAC_L^(GAMA-1)))
                         PRINT #GAS USING "#.### , ####.#",FRAC_L,VEL
70      NEXT A_BAR
80      PRINT #GAS,"  1. , 0."
        RETURN

90 END
```

```
10 REM^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
                                     CONDIA

                              H D CURCHACK            APR 1980
      ---------------------------------------------------------------------------

20       DIA=4  ! IN. !                      \        X_SEC_AREA=PI*DIA^2/4
         GAS$(1)="HELIUM"                    \        GAS$(2)="NITROGEN"
         SPEED(1)=3300    !FT/SEC!           \        SPEED(2)=1145
         DEG_OF_FREEDOM(1)=3                 \        DEG_OF_FREEDOM(2)=5
         GAMMA(1)=5/3                        \        GAMMA(2)=7/5
         TOTAL_L=94                          \        OUT$="#.####  , ####.#"

30 FOR GAS=1 TO 2
         N0=DEG_OF_FREEDOM(GAS)
         N1=N0+1
         N01=N0/N1
         C0=SPEED(GAS)
         PRINT GAS$(GAS)
         EXTEN$=LEFT$(GAS$(GAS),3)

         FILE$(1)="CONDIA."+EXTEN$
         FILE$(2)="BEGINCD."+EXTEN$
         FILE$(3)="CATCH."+EXTEN$
         OPEN FILE$(I) FOR OUTPUT AS FILE #GAS+I-1 FOR I=1 TO 2
         OPEN FILE$(3) FOR INPUT AS FILE #(GAS+2)
         GOSUB 40 FOR INIT_G=0 TO 3000 STEP 200
         CLOSE #GAS,#GAS+1,#GAS+2

         FILE$(1)="CONDIA1."+EXTEN$
         FILE$(2)="BEGINCD1."+EXTEN$
         FILE$(3)="CATCH1."+EXTEN$
         OPEN FILE$(I) FOR OUTPUT AS FILE #GAS+I-1 FOR I=1 TO 2
         OPEN FILE$(3) FOR INPUT AS FILE #(GAS+2)
         GOSUB 40 FOR INIT_G=0 TO 15000 STEP 3000
         CLOSE #GAS,#GAS+1,#GAS+2

   NEXT GAS
   GOTO 110

40       ! INFINITE RESERVOIR SUBROUTINE
         ! ----------------------------

         PRINT INIT_G
         IF INIT_G<>0
            THEN PRINT #GAS,"  0.  , 0."
                 FOR DRVR=0 TO TOTAL_L STEP 1
                        G_X_L=32.2*(TOTAL_L-DRVR) !(FT/SEC)SQUARE !
                        GOSUB 60
                        PRINT #GAS USING OUT$ ,DRVR/TOTAL_L,U0*C0
                 NEXT DRVR
50       INPUT #(GAS+2),FRAC_L,
         G_X_L=32.2*(1-FRAC_L)*TOTAL_L
         GOSUB 60
         PRINT #(GAS+1) USING OUT$,FRAC_L,U0*C0
```

```
      RETURN

60 ! DETERMINE VELOCITY WHICH IS IMPLICIT IN TERMS OF DISTANCE.

         Y0=G_X_L*INIT_G/C0^2
         F1=.T
         U0=SQR(Y0)
         IF U0>N0-1
            THEN U0=N0-1
70       X9=Y0/10000
         IF X9<1.00000E-07
            THEN X9=1.00000E-07

80       !                        LOOP

         X=N01 * (1- (1-U0/N01) / (1-U0/N0)^N1 )
         X1=Y0-X
         S0=SGN(X1)
         IF F2=S0
            THEN F2=0
                 F1=F1/2
90       IF ABS(X1)>X9
            THEN U0=(1+S0*(F1))*U0
                 F2=-S0
                 GO TO 80
         !                        END LOOP
100      RETURN

110 END
```

APPENDIX A

```
10 REM^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
                                   CATCH

            APRIL, 1980                                CURCHACK
______________________________________________________________________

       Compute point at which first reflected wave intercepts the
       projectile path.
       Elimination of the velocity at which the first wave overtakes
       the projectile (Seigel 13-7 by substitution into eq. 12-1)
       yields the distance that the wave overtakes the projectile.

  LET
       F=1-U*(GAMA-1)/(2*A)
  THEN
       F=(1+(GAMA+1)*X_D/2)^(-2*(GAMA-1)/(GAMA+1))          (13-7)
  HENCE
       X_B=2/(GAMA+1)*((2-(GAMA+1)*F)/(GAMA-1)/F^((GAMA+1)/(GAMA-1))+1)

       WHERE X_D AND X_B ARE THE DIMENSIONLESS DRIVER AND BARREL LENGTHS

20     DIAM=4  ! IN. !                  \       X_SEC_AREA=PI*DIAM^2/4
       TOTAL_L=94
       GAS$(1)="HELIUM"                 \       GAS$(2)="NITROGEN"
       SPEED(1)=3300    !FT/SEC!        \       SPEED(2)=1145
       DEG_OF_FREEDOM(1)=3              \       DEG_OF_FREEDOM(2)=5
       GAMA(1)=5/3                      \       GAMA(2)=7/5

30 FOR GAS=1 TO 2
       NO=DEG_OF_FREEDOM(GAS)
       PRINT GAS$(GAS)
       OPEN "CATCH."+LEFT$(GAS$(GAS),3) FOR OUTPUT AS FILE #GAS
       OPEN "CATCH1."+LEFT$(GAS$(GAS),3) FOR OUTPUT AS FILE #GAS+2
       F1_GAM=(GAMA(GAS)+1)/2
       F2_GAM=(GAMA(GAS)-1)/2
       C_SQ=SPEED(GAS)^2

       FYL=GAS
       GOSUB 40 FOR INIT_G=0 TO 3000 STEP 200
       CLOSE #FYL

       FYL=GAS+2
       GOSUB 40 FOR INIT_G=0 TO 15001 STEP 3000
       CLOSE #FYL
   NEXT GAS
   GOTO 90

40     ! OVERTAKE COMPUTATION
       ! --------------------

       PRINT "INITIAL G =";INIT_G        ! TERMINAL OUTPUT DURING EXECUTION
       D_START=0
       D_STEP=TOTAL_L/8
       RESOLUTE=0
       TRAVEL_D=0
```

```
50      FOR DRVR=D_START TO TOTAL_L STEP D_STEP
                X_D=32.2*DRVR*INIT_G/C_SQ

        !                REFLECTED WAVE COMPUTATION

                F=(1+F1_GAM*X_D)^(-2*F2_GAM/F1_GAM)
                X_B=((1-F1_GAM*F)/F^(F1_GAM/F2_GAM)/F2_GAM+1)/F1_GAM
                IF INIT_G<>0
                   THEN TRAVEL_D=X_B*C_SQ/(32.2*INIT_G)
60              CATCH_D=(TRAVEL_D+DRVR)/TOTAL_L
                IF CATCH_D<1
                   THEN 70
                   ELSE RESOLUTE=RESOLUTE+1
                        IF RESOLUTE>10
                           THEN 80
                           ELSE D_START=DRVR-D_STEP
                                D_STEP=D_STEP/2
                                GOTO 50
70      NEXT DRVR
80      FRAC_L=DRVR/TOTAL_L
        PRINT #FYL USING "#.####  , #.####  , #####", FRAC_L,CATCH_D,INIT_G
        RETURN

90 END
```

```
10 REM^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
                              CDPK.BAS

                    APR 80            H D CURCHACK
________________________________________________________________________________

        Read previously determined Pidduck-Kent velocity from the
        appropriate file, compute the infinite driver length velocity
        at the same relative length, then choose the value from the
        theory that predicts the lower velocity.  Once  the latter
        theory produces the lower velocity, only use that theory since
        Pidduck-Kent is no longer appropriate.

20      DIAM=4                              \      X_SEC_AREA=PI*DIAM^2/4
        GAS$(1)="HELIUM"                    \      GAS$(2)="NITROGEN"
        SPEED(1)=3300    !FT/SEC!           \      SPEED(2)=1145
        DEG_OF_FREEDOM(1)=3                 \      DEG_OF_FREEDOM(2)=5
        GAMMA(1)=5/3                        \      GAMMA(2)=7/5
        F$(1)="#.### , ####.#"              \      F$(2)=F$(1)+" , *"
        TOTAL_L=94

30 FOR GAS=1 TO 2
        N0=DEG_OF_FREEDOM(GAS)  \ PRINT GAS$(GAS)
        FX$=LEFT$(GAS$(GAS),3)

        OPEN "PK."+FX$ FOR INPUT AS FILE #(GAS+2)
        OPEN "CDPK."+FX$ FOR OUTPUT AS FILE #GAS
        OPEN "CDPKINT."+FX$ FOR OUTPUT AS FILE #(GAS+4)
        GOSUB 40 FOR INIT_G=200 TO 3000 STEP 200
        CLOSE #GAS,#(GAS+2),#(GAS+4)

        OPEN "PK1."+FX$ FOR INPUT AS FILE #(GAS+2)
        OPEN "CDPK1."+FX$ FOR OUTPUT AS FILE #GAS
        OPEN "CDPKINT1."+FX$ FOR OUTPUT AS FILE #(GAS+4)
        GOSUB 40 FOR INIT_G=3000 TO 15001 STEP 3000
        CLOSE #GAS,#(GAS+2),#(GAS+4)
   NEXT GAS
   GOTO 170

40      PRINT "INITIAL G =";INIT_G        ! TERMINAL OP DURING RUN
        V_FLAG=0
50      INPUT #GAS+2,FRAC_L,VEL
        DRVR=TOTAL_L*FRAC_L
        G_X_L=32.2*(TOTAL_L-DRVR)          !(FT/SEC)SQUARE !
        GOSUB 100
        NEW_VEL=U0*SPEED(GAS)    \ OUT_VEL=VEL
        IF V_FLAG=1
           THEN OUT_VEL=NEW_VEL
                GOTO 70
60      IF NEW_VEL<=VEL
           THEN OUT_VEL=NEW_VEL
                V_FLAG=1
                PRINT #(GAS+4) USING F$(1), FRAC_L,OUT_VEL
70      PRINT #GAS USING F$(1+V_FLAG), FRAC_L ,OUT_VEL
80      IF FRAC_L<1 THEN 50
```

```
90  RETURN

100      ! SUBROUTINE TO DETERMINE VELOCITY GIVEN A LENGTH FOR
         ! A CONSTANT DIAMETER GUN.      EQUATION IS
         ! IMPLICIT FOR VELOCITY AND EXPLICIT FOR LENGTH.

         Y0=G_X_L*INIT_G/SPEED(GAS)^2
         !-------------------------

110      F1=.1
         I=0
         U0=SQR(Y0)
         IF U0>N0-1
            THEN U0=N0-1
120      X9=Y0/10000
         IF X9<1.00000E-07
            THEN X9=1.00000E-07

         !                   LOOP

130 X=(N0/(N0+1)) * (1- (1-(N0+1)*U0/N0) / (1-U0/N0)^(N0+1) )
   !------------------------------------------------------------

         ! SEE FOR EXAMPLE EQ B11, HDL-TR-1330, CURCHACK
         X1=Y0-X
         S0=SGN(X1)
140      IF F2=S0
            THEN F2=0
                 F1=F1/2
150      IF ABS(X1)>X9
            THEN U0=(1+S0*(F1))*U0
                 F2=-S0
                 GO TO 130
160 RETURN                      ! END LOOP

170 END
```

```
10 REM^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
                              THEORY
               APR 80                              H D CURCHACK

          Range of Speeds vs Initial g for Isentropic Gun.
          Same for Constant Dia Gun. Outputs to separate files.
          Same for Pidduck-Kent Gun. Outputs to separate files.
   ___________________________________________________________________________

                              CONSTANTS

20        DIA=4   ! IN.                      \        X_SEC_AREA=PI*DIA^2/4

   SHORT=1                 \ REG=2                    \ LNG=3
   BARREL(SHORT)=59        \ BARREL(REG)=71           \ BARREL(LNG)=83
   DRIVER(SHORT)=35        \ DRIVER(REG)=23           \ DRIVER(LNG)=11
   RPP$(SHORT)=".SHO;1"    \ RPP$(REG)=".MED;1"       \ RPP$(LNG)=".LON;1"
   G_X_L(I)=32.2*BARREL(I) FOR I=SHORT TO LNG         ! (FT/SEC)SQUARE
   TOTAL_L=BARREL(SHORT)+DRIVER(SHORT)

          GAS$(1)="HELIUM"                   \        GAS$(2)="NITROGEN"
          SPEED(1)=3300   !FT/SEC!           \        SPEED(2)=1145
          DEG_OF_FREEDOM(1)=3                \        DEG_OF_FREEDOM(2)=5
          GAMMA(1)=5/3                       \        GAMMA(2)=7/5
          FORM2$="#.### , #.###"             \        FORM4$="####.# , ####.#"
          MAX_INIT_G(1)=5500                 \        MAX_INIT_G(2)=2750

30 FOR GAS=1 TO 2
          START_G=MAX_INIT_G(GAS)
          CO=SPEED(GAS)
          GAMA=GAMMA(GAS)
          NO=DEG_OF_FREEDOM(GAS)
          MORE$=LEFT$(GAS$(GAS),3)
          FOR BARREL%=SHORT TO LNG
                MY_FILE$="ISEN"+MORE$+RPP$(BARREL%)
                OPEN MY_FILE$ FOR OUTPUT AS FILE #GAS
                PRINT "FILE=";MY_FILE$
                FRAC_L=DRIVER(BARREL%)/TOTAL_L
                FRAC_L_FACT=NO*FRAC_L*(1-FRAC_L^(2/NO))/2
                FOR INIT_G=0 TO START_G STEP 25
                      YO=G_X_L(BARREL%)*INIT_G/CO^2
                      K=2*(YO*TOTAL_L/BARREL(BARREL%))
                      MACH_NO=SQR(K*FRAC_L_FACT)
                      PRINT #GAS USING FORM4$,INIT_G,MACH_NO*CO
40              NEXT INIT_G
                CLOSE #GAS

                MY_FILE$="COND"+MORE$+RPP$(BARREL%)
                OPEN MY_FILE$ FOR OUTPUT AS FILE #GAS
                PRINT "FILE=";MY_FILE$
                G_X_L(3)=G_X_L(BARREL%) !(FT/SEC)SQUARE !
50              FOR INIT_G=0 TO START_G STEP 25
                      RO=INIT_G/X_SEC_AREA
                      GOSUB 170
                      PRINT #GAS USING FORM4$, INIT_G , UO*CO
```

```
60              NEXT INIT_G
                CLOSE #GAS
70          NEXT BARREL%

            !              PIDDUCK-KENT THEORY
            !       SEE SEIGEL  HIGH SPEED GUNS PP 180-181

            OPEN "PIDD"+MORE$+RPP$(BRL%) FOR OUTPUT AS FILE #BRL%  &
                                                  FOR BRL%=1 TO 3
            FLAG(1)=0 \ FLAG(2)=0 \ FLAG(3)=0
            GAS_STEP(1)=.001 \ GAS_STEP(2)=.0025
            GOSUB 100
            CLOSE #1,#2,#3
80 NEXT GAS
90 GOTO 220

100 ! A_BAR IS A PARAMETER USED BY SEIGEL TO DETERMINE G/M AND VEL !
            THISSTEP=500 \ DEL_MU=1/THISSTEP
            FOR A_BAR=0 TO 1 STEP GAS_STEP(GAS)
            FOR SUMMY=0 TO THISSTEP-1
                    MU=SUMMY*DEL_MU
                    NUMU=MU+DEL_MU
                    DEL_AREA=(1-A_BAR*MU^2)^(NO/2)+(1-A_BAR*NUMU^2)^(NO/2)
                    INTGRAL=INTGRAL+DEL_AREA
            NEXT SUMMY
            INTGRAL=INTGRAL/2/THISSTEP
            G_OVER_M=(NO+2)*A_BAR*(1-A_BAR)^(-(NO+2)/2)*INTGRAL
110         FOR BRL%=SHORT TO LNG
                    FRAC_L=DRIVER(BRL%)/TOTAL_L
                    IF FLAG(BRL%)=1
                       THEN 130      ! DON'T COMPUTE IF INIT_G TOO LARGE
120                 INIT_G(BRL%) = G_OVER_M*CO^2/(GAMA*DRIVER_L*32.2)
                    VEL=2*CO/(GAMA-1)*SQR(A_BAR*(1-FRAC_L^(GAMA-1)))
                    IF INIT_G(BRL%)<=START_G
                       THEN PRINT #BRL% USING FORM4$,INIT_G(BRL%),VEL
                       ELSE FLAG(BRL%)=1
130         NEXT BRL%
140         INTGRAL=0
            IF INIT_G(1)>START_G
               THEN RETURN
150 NEXT A_BAR
160 RETURN

            !                   COMPUTATION SUBROUTINE

170         YO=G_X_L(3)*RO*X_SEC_AREA/CO^2
            F1=.1
            I=0
            UO=SQR(YO)
            IF UO>NO-1
               THEN UO=NO-1
180         X9=YO/10000
            IF X9<1.00000E-07
               THEN X9=1.00000E-07
```

```
        !                             LOOP

190     X=(N0/(N0+1)) * (1- (1-(N0+1)*U0/N0) / (1-U0/N0)^(N0+1) )
        I=I+1
        X1=Y0-X
        S0=SGN(X1)
        IF F2=S0
           THEN F2=0
                F1=F1/2
200     IF ABS(X1)>X9
           THEN U0=(1+S0*(F1))*U0
                F2=-S0
                GO TO 190

        !                             END LOOP

210 RETURN
220 END
```

```
10 REM^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^&
&                          WTVSRPP.BAS                                   &
&
   ------------------------------------------------------------------------

        The isentropic expansion theory permits ready estimation of
        the quantity of gas (proportional to G.OVER.M) required
        to produce a given velocity as a function of the relative
        pin position (FRAC.L).  Note that G.OVER.M is a monotonic
        function of FRAC.L.

                - CONVERT G.OVER.M TO INIT.G AND DRIVER.L -
                  CO^2=GAMA*P/RHO
        ALSO
                  WEIGHT OF GAS (G)=RHO*X.SEC.A*DRIVER.L
                  DRIVER.L=G/(RHO*X.SEC.A)
                          =G*CO^2/(GAMA*P*X.SEC.A)
                          =G*CO^2/(GAMA*INIT.G*M)
        THEREFORE
                  DRIVER.L=G.OVER.M*CO^2/(GAMA*INIT.G*32.2)

15      DIM FR(200),GOM(8,200)
20      GAS$(1)="HELIUM"                \     GAS$(2)="NITROGEN"
        GAMMA(1)=5/3                    \     GAMMA(2)=7/5
        SPEED(1)=3300   !FT/SEC!        \     SPEED(2)=1145
        F1$="#.###  #.###### #.###### #.###### #.######" + &
                                        " #.###### #.###### #.###### #.######"
30 FOR GAS=1 TO 2
        PRINT GAS$(GAS);
        GAMA=GAMMA(GAS)
        GAM1=GAMA-1
        GAM2=GAMA*GAM1/2 \ PRINT "FACTOR GAM2 =";GAM2
        MAX.L=.8
        K=0
        FOR VELOCITY=300 TO 1000 STEP 100
                K=K+1
                KK=0
                MACH.NO=VELOCITY/SPEED(GAS)
                FACT1=MACH.NO^2 * GAM2 \ PRINT VELOCITY,FACT1
                FOR FRAC.L=0 TO MAX.L STEP .005
                        G.OVER.M=FACT1 / (1-FRAC.L^GAM1)
                        IF G.OVER.M <=1
                           THEN KK=KK+1
                                GOM(K,KK)=G.OVER.M
                                FR(KK)=FRAC.L
                           ELSE GOTO 37
            35  NEXT FRAC.L
37      NEXT VELOCITY
        OPEN "WTVSRPPO."+LEFT$(GAS$(GAS),3) FOR OUTPUT AS FILE #GAS
        MARGIN #GAS,100
        PRINT #GAS USING F1$,FR(J),GOM(8,J),GOM(7,J),GOM(6,J), &
                GOM(5,J),GOM(4,J),GOM(3,J),GOM(2,J),GOM(1,J) FOR J=1 TO KK
        CLOSE #GAS
   NEXT GAS
40 END
```

```
10      REM^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
                            NRG.BAS

        Computation of fraction of gas energy converted to projectile
        energy based on Lagrange theory.  Function only of Z (or RPP)
        and N (degrees of freedom).

        ____________________________________________________________

        Using gas energy per unit mass, e = N R T / 2
        and                             P = RHO R T
        and total gas energy,        Egas = e RHO Volume
        and                        volume = A x.
        Then                         Egas = (N R T / 2) X RHO A x
        or                           Egas = N P A x / 2.
        .                                       2
        Also                        Ebird = M U  / 2
        .                                              2/N
        and from eql of text        Ebird = Egas (1 - Z    )

        .                                         2/N
        Therefore,           Ebird / Egas = 1 - Z

20      DEF FNA(Z,N)=(1-Z^(2/N))
30      FORM$="#.####  #.#####  #.#####"
35      OPEN "ENERGY.DAT" FOR OUTPUT AS FILE #1
40      PRINT #1 USING FORM$,Z,FNA(Z,3),FNA(Z,5) FOR Z=0 TO .049 STEP .005
50      PRINT #1 USING FORM$,Z,FNA(Z,3),FNA(Z,5) FOR Z=.05 TO 1 STEP .025
60      END
```

DISTRIBUTION

ADMINISTRATOR
DEFENSE TECHNICAL INFORMATION CENTER
ATTN DTIC-DDA (12 COPIES)
CAMERON STATION, BUILDING 5
ALEXANDRIA, VA 22314

COMMANDER
US ARMY RSCH & STD GP (EUR)
ATTN CHIEF, PHYSICS & MATH BRANCH
FPO NEW YORK 09510

COMMANDER
US ARMY MATERIEL DEVELOPMENT
& READINESS COMMAND
ATTN DRCDE-S, PROGRAM SUPPORT OFFICE
ATTN DRCQA, DIR FOR QUALITY ASSURANCE
ATTN DRCSF-E, ENGINEERING
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

COMMANDER
US ARMY MISSILE & MUNITIONS CENTER
& SCHOOL
ATTN ATSK-CTD-F
REDSTONE ARSENAL, AL 35809

DIRECTOR
US ARMY MATERIEL SYSTEMS ANALYSIS
ACTIVITY
ATTN DRXSY-MP
ABERDEEN PROVING GROUND, MD 21005

DIRECTOR
US ARMY BALLISTIC RESEARCH LABORATORY
ATTN DRDAR-TSB-S (STINFO)
ATTN RURIK LODER
ATTN JIM EVANS
ATTN DEVELOPMENT & PROOF SERVICES,
SAUL TARAGIN
ATTN INTERIOR BALLISTICS LABORATORY
ATTN SIGNATURE & PROPAGATION LABORATORY
ATTN DRXBR-BB, V. RICHARD
ATTN DRXBR-BB, J. PILCHER
ATTN DRXBR-EB, W. MERMAGEN
ATTN DRXBR-EB, E. BOYER
ATTN STEAP-TL, TECHNICAL LIBRARY DIVISION
(2 COPIES)
ATTN E. BOYER, CHIEF,
TRANSONIC RANGE FACILITY
ABERDEEN PROVING GROUND, MD 21005

US ARMY ELECTRONICS TECHNOLOGY
& DEVICES LABORATORY
ATTN DELET-DD
FT MONMOUTH, NJ 07703

HQ USAF/SAMI
WASHINGTON, DC 20330

TELEDYNE BROWN ENGINEERING
CUMMINGS RESEARCH PARK
ATTN DR. MELVIN L. PRICE, MS-44
HUNTSVILLE, AL 35807

ENGINEERING SOCIETIES LIBRARY
345 EAST 47TH STREET
ATTN ACQUISITIONS DEPARTMENT
NEW YORK, NY 10017

US LIBRARY OF CONGRESS
SCIENCE & TECHNOLOGY DIVISION
WASHINGTON, DC 20540

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
ATTN LIBRARY
ATTN DR. GALEN B. SCHUBAUER
WASHINGTON, DC 20234

BOULDER LABORTORIES
NATIONAL BUREAU OF STANDARDS
ATTN LIBRARY
BOULDER, CO 90302

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
COMMITTEE ON UNDERSEA WARFARE
2102 CONSTITUTION AVENUE, NW
WASHINGTON, DC 20418

NATIONAL AERONAUTICS & SPACE
ADMINISTRATION
LEWIS RESEARCH CENTER
ATTN GEORGE MANDEL, CHIEF, LIBRARY
21000 BROOKPARK ROAD
CLEVELAND, OH 44135

NATIONAL AERONAUTICS & SPACE
ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
ATTN LIBRARY
GREENBELT, MD 20771

NATIONAL AERONAUTICS & SPACE
ADMINISTRATION
LANGLEY RESEARCH CENTER
LANGLEY STATION
ATTN LIBRARY, MS 185
ATTN MITCHEL H. BERTRAM, MD 243
ATTN RUSSELL HOPKO, PARD, MS 213
HAMPTON, VA 23365

NATIONAL AERONAUTICS & SPACE
ADMINISTRATION
ATTN DR. H. H. KURWEG, DIRECTOR
OF RESEARCH
600 INDEPENDENCE AVENUE, SW
WASHINGTON, DC 20546

NASA/AMES RESEARCH CENTER
ATTN CHARLES DE ROSE,
MAIL STOP N237-1
MOFFETT FIELD, CA 94035

OFFICE OF THE UNDERSECRETARY OF DEFENSE
FOR RESEARCH & ENGINEERING
ATTN TECHNICAL LIBRARY
THE PENTAGON
WASHINGTON, DC 20301

OFFICE OF THE DEPUTY CHIEF OF STAFF FOR
RESEARCH, DEVELOPMENT & ACQUISITION
DEPARTMENT OF THE ARMY
ATTN DAMA-ARZ-A, DIRECTOR OF ARMY RESEARCH
WASHINGTON, DC 20310

DEFENSE RESEARCH ESTABLISHMENT
VALCARTIER
DEFENSE RESEARCH BOARD
ATTN DIRECTOR OF R&D
QUEBEC, CANADA

COMMANDER
EUSTIS DIRECTORATE
US ARMY AIR MOBILITY RESEARCH &
DEVELOPMENT LABORATORY
ATTN DIRECTOR, R&D
FT EUSTIS, VA 23604

ARMY ADVANCED BALLISTICS MISSILE
DEFENSE AGENCY
PO BOX 5475
ATTN TECH DIRECTOR
RIVERSIDE, CA 92507

COMMANDER
US ARMY MOBILITY EQUIPMENT RESEARCH
& DEVELOPMENT CENTER
ATTN TECHNICAL LIBRARY
FT BELVOIR, VA 22060

COMMANDER
US ARMY ARMAMENT RESEARCH & DEVELOPMENT
COMMAND
ATTN DRDAR-TS, TECHNICAL SUPPORT DIV
DOVER, NJ 07801

COMMANDER
US ARMY MATERIALS & MECHANICS
RESEARCH CENTER
ATTN DRXMR-PL, TECHNICAL LIBRARY
ATTN DRXMR-T, MECHANICS & ENGINEERING
LABORATORY
ATTN TECHNICAL INFORMATION OFFICE
WATERTOWN, MA 02172

COMMANDER
US ARMY MATERIEL SYSTEMS ANALYSIS
ACTIVITY
ATTN X5 (W3JCAA)
ABERDEEN PROVING GROUND, MD 21005

CHIEF
ARMY RESEARCH OFFICE (DURHAM)
PO BOX 12211
ATTN DRXRO-EG, DIR ENGINEERING DIV
ATTN CRD-AA-IP
RESEARCH TRIANGLE PARK, NC 27709

COMMANDER
YUMA PROVING GROUND
ATTN STEYP-TE, TEST & EVALUATION
DIRECTORATE
YUMA PROVING GROUND, AZ 85364

COMMANDER
US ARMY TANK-AUTOMOTIVE COMMAND
ATTN NICP, DIRECTORATE FOR MATERIEL
MANAGEMENT
ATTN SMOTA-RCS, PHYSICAL SCIENCES
LABORATORY
ATTN SMOTA-RCF, FIRE POWER LABORATORY
WARREN, MI 48090

COMMANDER
US ARMY WEAPONS COMMAND
ATTN LIBRARY
ROCK ISLAND, IL 61201

COMMANDER
ARRADCOM HQ
ATTN SCIENTIFIC & TECHNICAL INFORMATION
BRANCH
ATTN W. HADOWANETZ
ATTN R. BUXTON
ATTN S. KOCH
ATTN F. SAXE, BLDG 3359,
LIGHT WEAPONS
ATTN DR-DAR-SCA
DOVER, NJ 07801

COMMANDER
EDGEWOOD ARSENAL
ATTN TECHNICAL LIBRARY
EDGEWOOD ARSENAL, MD 21010

SUPERINTENDENT
NAVAL POSTGRADUATE SCHOOL
ATTN LIBRARY, CODE 2124
MONTEREY, CA 93940

COMMANDER
NAVAL SURFACE WEAPONS CENTER
ATTN GUN SYSTEMS & MUNITIONS DIV
ATTN TECHNICAL LIBRARY
WHITE OAK, MD 20910

DEPARTMENT OF THE NAVY
ORDNANCE SYSTEM COMMAND
ATTN DLI-E, TECHNICAL LIBRARY
WASHINGTON, DC 20360

DIRECTOR
NAVAL RESEARCH LABORATORY
ATTN CODE 2600, TECH INFO DIV
ATTN CODE 2620, TECH LIBRARY
ATTN CODE 2027, LIBRARY
ATTN CODE 2029, (ONRL)
WASHINGTON, DC 20375

COMMANDER
NAVAL WEAPONS CENTER
ATTN TECH LIBRARY
ATTN CODE 2027, LIBRARY
ATTN CODE 406, TECH LIB
CHINA LAKE, CA 93555

COMMANDER
US NAVAL SURFACE WEAPONS CENTER
ATTN LEON ANDERSON
ATTN LIBRARY
ATTN CODE KE
ATTN CODE TX
DAHLGREN, VA

DIRECTOR
US NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CA 92152

US NAVAL ACADEMY
ENGINEERING DEPARTMENT
ATTN LIBRARY
ANNAPOLIS, MD 21402

COMMANDER
US NAVAL AIR DEVELOPMENT CENTER
ATTN TECH LIBRARY
WARMINSTER, PA 18974

COMMANDER
NAVAL UNDERSEA CENTER
ATTN DIR A. G. FABULA, CODE 6005
SAN DIEGO, CA 92132

OFFICER-IN-CHARGE
NAVAL UNDERSEA CENTER
3203 E. FOOTHILL BOULEVARD
PASADENA, CA 91107

CHIEF OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
ATTN CODE 463
ATTN CODE 438
ATTN CODE 439
ARLINGTON, VA 22217

COMMANDER
NAVAL AIR SYSTEMS COMMAND
DEPARTMENT OF THE NAVY
ATTN AIR-03B
ATTN AIR-5203
ATTN AIR-5301
ATTN AIR-5302
WASHINGTON, DC 20361

COMMANDER
NAVAL SEA SYS COMMAND, HQ
DEPARTMENT OF THE NAVY
ATTN NSEA-03A
ATTN NSEA-035B
ATTN NSEA-541
ATTN NSEA-0521
ATTN NSEA-0532
2521 JEFFERSON DAVIS HIGHWAY
ARLINGTON, VA 20360

COMMANDING OFFICER
NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CA 93041

COMMANDER
DAVID W. TAYLOR NAVAL SHIP
RESEARCH & DEVELOPMENT CENTER
ATTN ELIZABETH DEMPSEY, CODE 534
ATTN PAUL GRANVILLE, CODE 581
ATTN G. H. FRANZ
ATTN WILLIAM R. HOOVER
ATTN R. J. GRADY
ATTN D. CIESLOWSKI
ATTN STRUCTURES
BETHESDA, MD 20084

COMMANDING OFFICER
US NAVAL MISSILE CENTER
ATTN TECHNICAL LIBRARY, CODE NO322
POINT MUGU, CA 93041

US NAVAL RESEARCH LABORATORY
ATTN ANDREW E. WILLIAMS CODE 7908
WASHINGTON, DC 20375

AIR FORCE WEAPONS LABORATORY/DYC
WLRP
ATTN CAPT R. G. HENNING
KIRTLAND AIR FORCE BASE, NM 87117

DEPUTY CHIEF OF STAFF
RESEARCH & DEVELOPMENT
HEADQUARTERS, US AIR FORCE
ATTN AFRDQSM
WASHINGTON, DC 20330

AF AERO-PROPULSION LABORATORY
WRIGHT-PATTERSON AFB, OH 45433

ARVIN/CALSPAN FIELD SERVICES
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
ATTN HENRY W. BALL
ARNOLD AIR FORCE STATION, TN 37389

AIR FORCE ARMAMENT LABORATORY
AFATL/DLDL
ATTN GERALD L. WINCHENBACH
EGLIN AFB, FL 32542

COMMANDER
ARMAMENT DEVELOPMENT & TEST
CENTER
EGLIN AFB, FL 32542

COMMANDER
AF FLIGHT DYNAMICS LAB
ATTN PTS SURVIVABILITY/VULNERABILITY
BRANCH
WRIGHT-PATTERSON AFB, OH 45433

COMMANDER
ARNOLD ENGINEERING DEVELOPMENT CENTER
ATTN CAPT CARLOS TIRRES, DYR
ATTN DY, DIR TECHNOLOGY
ATTN LIBRARIAN
ARNOLD AIR FORCE STATION, TN 37389

AF OFFICE OF SCIENTIFIC RESEARCH
ATTN LIBRARIAN
BOLLING AFB, DC 20332

6585TH TEST GROUP
TEST TRACK DIVISION
ATTN D. J. KRUPOVAGE G585TG/TKE
HOLLOMAN AFB, NM 88330

COMMANDER
NATICK LABORATORIES
ATTN DIRECTOR, R&D
NATICK, MA 01762

AAI
PO BOX 6767
MAIL STOP: E 156
ATTN MR. C. CHANDLER
BALTIMORE, MD 21204

ALLEGHANY BALLISTICS LABORATORY
HERCULES POWDER CO
ATTN CAPT N. J. KLEISS
CUMBERLAND, MD 12502

AEROSPACE CORP
PO BOX 95085
ATTN DR. J. S. WHITTIER
ATTN M. J. ADAMS
LOS ANGELES, CA 90045

AVCO-EVERETT RESEARCH LABORATORY
ATTN DR. ARTHUR KANTROWITZ
885 REVERE BEACH PARKWAY
EVERETT, MA 02149

AVCO SYSTEMS DIVISION
ATTN WILLIAM L. MCKAY
201 LOWELL STREET
WILMINGTON, MA 01887

AEROPHYSICS COMPANY
ATTN GABRIEL D. BOEHLER
3500 CONNECTICUT AVENUE, NW
WASHINGTON, DC 20003

BOEING COMPANY
RESEARCH & ENGINEERING DIV
ATTN LIBRARIAN
SEATTLE, WA 98100

BATTELLE MEMORIAL INSTITUTE
ATTN REMOTE AREA CONFLICT
INFORMATION CENTER
505 KING AVENUE
COLUMBUS, OH 43201

BULOVA
PO BOX 189
ATTN S. SUGARMAN
GREEN ACRES ROAD WEST
VALLEY STREAM, NY 11582

BOEING COMPANY
AEROSPACE COMPANY
PO BOX 3707
ATTN 8K-38, RUTH E. PERRENBOOM
SEATTLE, WA 98124

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
PO BOX 1663
ATTN REPORT LIBRARY
LOS ALAMOS, NM 97544

CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY
ATTN T. KICENIUK,
HYDRODYNAMICS LABORATORY
ATTN PROF M. S. PLESSET, DIV OF
ENGINEERING
ATTN PROF T. Y. WU
PASADENA, CA 91103

THE CATHOLIC UNIVERSITY OF AMERICA
DEPARTMENT OF SPACE SCIENCE & APPLIED
PHYSICS
ATTN DR. C. C. CHANG
WASHINGTON, DC 20017

CORNELL UNIVERSITY
SCHOOL OF CHEMICAL ENGINEERING
GRUMAN HALL
ATTN E. L. RESLER, JR.
ITHACA, NY 14850

COLORADO STATE UNIVERSITY
ATTN CIVIL ENGINEERING HYDRAULICS
LABORATORY
FT COLLINS, CO 80521

CIVIL ENGINEERING RESEARCH FACILITY
UNIVERSITY OF NEW MEXICO
PO BOX 188
ALBUQUERQUE, NM 87131

UNIVERSIY OF CALIFORNIA
DEPARTMENT OF NAVAL ARCHITECTURE
ATTN PROF J. V. WEHAUSEN
BERKELEY, CA 94720

COMMISSARIAT A L'ENERGIE ATOMIQUE
CENTRE D'ETUDES DE LIMEIL - BP27
ATTN DR. HENRI BERNIER
94190 VILLENEUVE SAINT-GEORGES
FRANCE

CALIFORNIA INSTITUTE OF TECHNOLOGY
SEISMOLOGICAL LABS 252-21
ATTN WARREN GINN
PASADENA, CA 91125

DYNASEN, INC
20 DEAN ARNOLD PLACE
ATTN DR. JACQUES CHAREST
GOLETA, CA 93017

DEFENSE RESEARCH ESTABLISHMENT
VAL CARTIER
PO BOX 880
COURCELETTE P.Q.
ATTN GEDEON DUROIN
CANADA GIV3K6

DIR. DIPL-ING. H. SCHULTE
ERP ST. 91 D. BW
ATTN DR. J. K. BIELE
4470 MEPPEN
FEDERAL REPUBLIC OF WEST GERMANY

UNIVERSITY OF DAYTON RESEARCH INSTITUTE
ATTN STEPHAN BLESS
300 COLLEGE PARK DRIVE
DAYTON, OH 45469

UNIVERSITY OF DELAWARE
MECHANICAL & AERONAUTICAL
ENGINEERING DEPARTMENT
ATTN DR. JAMES DANBERG
NEWARK, NJ 19711

DIRECTOR
DEFENSE ADVANCED RESEARCH
PROJECTS AGENCY
ARCHITECT BLDG
ATTN MATERIALS SCIENCES
ATTN ADVANCED CONCEPTS DIV
ATTN TARGET ACQUISITION & ENGAGEMENT DIV
ATTN WEAPONS TECH & CONCEPTS DIV
1400 WILSON BLVD
ARLINGTON, VA 22209

ERNST-MACH-INSTITUT
DER FRAUNHOFER-GESELLSCHAFT
ECKERSTRASSE 4
D 7800 FREIBURG I. BR.
ATTN DR. ALOIS STILP
FEDERAL REPUBLIC OF WEST GERMANY

EASTMAN KODAK CO
ATTN G. MONGEAU
901 ELMGROVE ROAD
ROCHESTER, NY 14650

EFFECTS TECHNOLOGY, INC
ATTN WILLIAM M. ISBELL
5383 HOLLISTER AVENUE
SANTA BARBARA, CA 93111

FRANKLIN INST RESEARCH LABS
ATTN TECHNICAL DIRECTOR
20TH & BENJAMIN FRANKLIN PARKWAY
PHILADELPHIA, PA 19103

FORSVARETS FORSKNINGSANSTALT
NATIONAL DEFENSE RESEARCH INSTITUTE
LINNEGATON 89, STOCKHOLM
ATTN SVEN NORDSTORM
FMV-F:AP/FOA 276
S-546 01 KARLSBORG SWEDEN
S-104 50 STOCKHOLM
SWEDEN

GENERAL ELECTRIC CO/ARMAMENT
SYSTEMS DEPT.
LAKESIDE AVENUE
ATTN ROBERT WHYTE, RM 1311
BURLINGTON, VT 05402

GM/DRL DELCO ELECTRONICS SBO
ATTN DR. F. K. BOUTWELL
6767 HOLLISTER AVENUE
GOLETA, CA 93017

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATTN HYDRAULICS LABORATORY
225 NORTH AVENUE, NW
ATLANTA, GA 30332

GOODYEAR AEROSPACE CORP
ATTN LIBRARIAN
AKRON, OH

GENERAL DYNAMICS
POMONA DIVISION
MAIL ZONE 4-53
ATTN D. STARBUCK
1675 WEST MISSION BLVD
POMONA, CA 91766

GENERAL DYNAMICS
ELECTRIC BOAT DIVISION
MARINE TECHNOLOGY CENTER
PO BOX 911
ATTN W. B. BARKLEY
ATTN DR. BLANE R. PARKIN,
MAIL ZONE 6-116
SAN DIEGO, CA 92112

GENERAL ELECTRIC CO
SPACE DIVISION
PO BOX 8555
ATTN LAWRENCE I. CHASEN,
MANAGER/MSC LIBRARIES
ATTN ANTHONY P. COPPA
ATTN R. F. PAPA
PHILADELPHIA, PA 19101

GENERAL ELECTRIC CO
RE-ENTRY & ENVIRONMENTAL SYSTEMS
DIVISION
PO BOX 7722
ATTN W. DASKIN, MANAGER, TECHNOLOGY
ENGINEERING SECTION
ATTN W. W. WILSON, MANAGER MILITARY
OCEAN PROGRAMS
PHILADELPHIA, PA 19101

GENERAL ELECTRIC CO
VALLEY FORGE SPACE TECHNOLOGY CENTER
ATTN L. MARSHALL
ATTN DR. R. F. HOPPMANN
KING OF PRUSSIA, PA 19406

GENERAL MOTORS
TECHNICAL CENTER
ATTN LIBRARIAN
WARREN, MI 48090

HYDRONAUTICS, INC
ATTN P. EISENBERG
ATTN M. P. TULIN
PINDELL SCHOOL ROAD
HOWARD COUNTY
LAUREL, MD 20810

HONEYWELL ORDNANCE DIVISION
ATTN E. M. JOHNSON
ATTN P. T. KERSH
ATTN S. SOPSZAK
600 2ND STREET, N
HOPKINS, MN 53343

HEXCEL CORPORATION
LOYOLA FEDERAL BLDG
ATTN T. EMERSON
BEL AIR, MD 21014

INSTITUT FUER LUFT UND RAUMFAHRT
TECHNISCHE UNIVERSITAET
ATTN DR. E. IGENBERGS
8000 MUENCHEN 2
ARCISSTRASSE 21
FEDERAL REPUBLIC OF GERMANY

IIT RESEARCH INSTITUTE
ATTN LIBRARIAN
10 W. 35TH STREET
CHICAGO, IL 60616

INSTITUT FRANCO-ALLEMAND
DE RECHERCHES DE SAINT-LOUIS
ATTN M GIRAUD
12, RUE DE L'INDUSTRIE
68301 SAINT-LOUIS
FRANCE

THE UNIVERSITY OF IOWA
THE INSTITUTE OF HYDRAULIC RESEARCH
ATTN HUNTER ROUSE
ATTN LOUIS LANDWEBER
IOWA CITY, IQ 52240

UNIVERSITY OF ILLINOIS
COLLEGE OF ENGINEERING
DEPARTMENT OF THEORETICAL &
APPLIED MECHANICS
ATTN DR. J. M. ROBERTSON
212 TALBOT LABORATORY
URBANA, IL 61801

JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
ATTN DR. L. L. CRONVICH
ATTN DOCUMENT LIBRARIAN
ATTN L. B. WECKESSER
8621 GEORGIA AVENUE
SILVER SPRING, MD 20910

JET PROPULSION LABORATORY
ATTN LIBRARY, TDS- N.E. DEVERAUX
4800 OAK GROVE DRIVE
PASADENA, CA 91103

KAMAN SCIENCES CORP
KAMAN NUCLEAR DIVISION
PO BOX 7463
ATTN DR. A. P. BRIDGES
COLORADO SPRINGS, CO 80901

DEPARTMENT OF MECHANICAL ENGINEERING
KYOTO UNIVERSITY
ATTN PROF TOSHIRO YAMADA
SAKYO-KU, KYOTO 606
JAPAN

LAWRENCE LIVERMORE NATIONAL LABORATORY
PO BOX 808
ATTN CHARLES HONODEL L-368
LIVERMORE, CA 94550

LABORATOIRE DE RECHERCHES BALISTIQUES
ET AERODYNAMIQUES
ATTN J. DUMAS
27207 VERNON, BP 914
FRANCE

DIRECTOR
LAWRENCE RADIATION LABORATORY
PO BOX 1663
ATTN LIBRARIAN
LOS ALAMOS, NM 87544

LOCKHEED MISSILES & SPACE CO
MISSILE SYSTEMS DIVISION
PO BOX 504
ATTN R. W. KERMEEN, DEPT 50-35,
BLDG 153 F/1
ATTN FRANK CHAPMAN, DEPT 81-90
SUNNYVALE, CA 94086

UNIVERSITY OF MARYLAND
DEPARTMENT OF AEROSPACE ENGINEERING
GLEN L. MARTIN INSTITUTE OF TECHNOLOGY
ATTN PROF JOHN D. ANDERSON, JR.
COLLEGE PARK, MD 20742

UNIVERSITY OF MARYLAND
MECHANICAL ENGINEERING DEPARTMENT
ATTN DR. C. L. SAYRE
ATTN DR. JAMES DALLY
COLLEGE PARK, MD 20742

UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC
ATTN PROF E. SILBERMAN
MISSISSIPPI RIVER AT 3RD AVE WE
MINNEAPOLIS, MN 55141

MARTIN MARIETTA CORP
AEROSPACE DIV
PO BOX 5837
M.D.109
ATTN LIBRARIAN
ORLANDO, FL 32805

MOTOROLA INC
ATTN G. GARDNER
8201 EAST MCDOWELL RD
SCOTTSDALE, AZ 85252

NORTH AMERICAN AVIATION INC
SPACE & INFORMATION SYSTEMS DVISION
ATTN TECHNICAL INFORMATION CENTER,
D/096-722 (AJ01)
DOWNEY, CA 90241

STATE UNIVERSITY OF NEW YORK AT BUFFALO
DEPARTMENT OF MECHNICAL ENGINEERING
FACULTY OF ENGINEERING & APPLIED SCIENCES
PARK ENGINEERING BUILDING
ATTN J. GORDON HAL
BUFFALO, NY 14212

OHIO STATE UNIVERSITY
DEPARTMENT OF AERO-ASTRONAUTICAL
ENGINEERING
ATTN PROF TING YI LI
2036 NEIL AVENUE
COLUMBUS, OH 43210

OCEANICS, INC
ATTN DR. PAUL KAPLAN
PLAINVIEW LONG ISLAND, NY 11803

DIRECTOR ORDNANCE RESEARCH LABORATORY
PENNSYLVANIA STATE UNIVERSITY
PO BOX 30
STATE COLLEGE, PA 16801

PHYSICS INTERNATIONAL COMPANY
2700 MERCED STREET
SAN LEANDRO, CA 94577

PRINS MAURITS LABORATORY
TNO
PO BOX 45
ATTN DR. W. J. KOLKERT
2280 AA RIJSWIJK
THE NETHERLANDS

ROYAL ARMAMENT RESEARCH &
DEVELOPMENT ESTABLISHMENT
BALLISTICS BRANCH R31
ATTN P. W. W. FULLER
FT HALSTEAD, SEVENOAKS
KENT, ENGLAND

SCIENCE APPLICATIONS, INC
ATTN GEORGE BURGHART
201 WEST DYER ROAD
UNIT B
SANTA ANA, CA 92707

SANDIA LABORATORIES
PO BOX 5800
ATTN S. FLUENT
ATTN TECHNICAL LIBRARY
ATTN W. V. HEREFORD, DIV 7215
ATTN R. C. MAYDEW, AERO-THERMODYNAMICS DEPT
ATTN DIVISION 5534
LALIT C. CHHABILDAS
ALBUQUERQUE, NM 87185

SANDIA LABORATORIES
LIVERMORE LABORATORY
PO BOX 969
ATTN TECHNICAL REFERENCE LIBRARY
LIVERMORE, CA 04550

SOUTHWEST RESEARCH INSTITUTE
PO DRAWER 28510
ATTN LIBRARY
ATTN ALEX B. WENZEL
SAN ANTONIO, TX 78284

STANFORD UNIVERSITY
ATTN PROF E. Y. HSU
ATTN DR. DANIEL BERSHADER
DEPT OF AERONAUTICAL & ASTRONAUTICAL
STANFORD, CA 94305

STEVENS INSTITUTE OF TECHNOLOGY
DAVIDSON LABORATORY
ATTN DR. ALBERT STRUMPF
ATTN ANTHONY SURAEZ
HOBOKEN, NJ 07030

SYSTEMS, SCIENCE & SOFTWARE
PO BOX 1620
ATTN LIBRARIAN
LA JOLLA, CA 92037

TOKYO INSTITUTE OF TECHNOLOGY
RESEARCH LAB OF ENGR MATERIALS
ATTN DR. A. SAWAOKA
4259 NAGATSUTA, MIDORI
YOKOHAMA 227, JAPAN

TERA TEK, INC
UNIVERSITY OF UTAH RESEARCH PARK
ATTN SIDNEY GREEN
420 WAKARA WAY
SALT LAKE CITY, UT 84108

THERM ADVANCED RESEARCH, INC
100 HUDSON CIRCLE
ITHACA, NY 14851

UNITED AIRCRAFT CORP
RESEARCH LABORATORY
ATTN J. J. CHARETTE
ATTN F. S. OWEN
EAST HARTFORD, CT 06108

UNIVERSITY OF UTAH
COLLEGE OF ENGINEERING
ATTN PROF MAX L. WILLIAMS, DEAN
SALT LAKE CITY, UT 84112

WASHINGTON STATE UNIVERSITY
R. L. ALBROOK HYDRAULIC LABORATORY
DIVISION OF INDUSTRIAL RESEARCH
ATTN CHAIRMAN, MECHANICAL ENGINEERING DEPT
PULLMAN, WA 91634

WORCESTER POLYTECHNIC INSTITUTE
ALDEN RESEARCH LABORATORY
ATTN PROF L. J. HOOPER
ATTN L. C. NEALE
WORCESTER, MA 01609

UNIVERSITY OF WYOMING
COLLEGE OF ENGINEERING
UNIVERSITY STATION, BOX 3295
ATTN ENGINEERING LIBRARY
ATTN PROF JAMES D. MATHENY
HEAD DEPT OF MECHANICAL ENGINEERING
LARAMIE, WY 82070

UNIVERISTY OF WEST FLORIDA
FACULTY OF AERONAUTICAL SYSTEMS
ATTN DR. RICHARD FLEDDERMAN
PENSACOLA, FL 32504

US ARMY ELECTRONICS RESEARCH & DEVELOPMENT COMMAND
ATTN TECHNICAL DIRECTOR, DRDEL-CT

HARRY DIAMOND LABORATORIES
ATTN CO/TD/TSO/DIVISION DIRECTORS
ATTN RECORD COPY, 81200
ATTN HDL LIBRARY, 81100 (2 COPIES)
ATTN HDL LIBRARY, 81100 (WOODBRIDGE)
ATTN TECHNICAL REPORTS BRANCH, 81300
ATTN CHAIRMAN, EDITORIAL COMMITTEE
ATTN LEGAL OFFICE, 97000
ATTN MORRISON, R. E., 13500
ATTN NELSON, F., 48500
ATTN POLLIN, I., 48500
ATTN MARY, D., 48500
ATTN MCINTOSH, W., 48500
ATTN MARCUS, I., 48000
ATTN FURLANI, J., 48100
ATTN BEARD, J., 34200
ATTN CURCHACK, H. D., 48500 (25 COPIES)